CRANFIELD UNIVERSITY

MAKSIM MAKSIMOVIC

LEAN KNOWLEDGE LIFE CYCLE FRAMEWORK TO SUPPORT LEAN PRODUCT DEVELOPMENT

SCHOOL OF APPLIED SCIENCES

PhD

Academic Year: 2010 - 2013

Supervisors: Dr Essam Shehab and Dr Ahmed Al-Ashaab

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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

This research thesis presents the development of a novel Lean Knowledge Life Cycle (LeanKLC) framework to support the transformation into a Lean Product Development (LeanPD) knowledge environment. The LeanKLC framework introduces a baseline model to understand the three dimensions of knowledge management in product development as well as its contextualisation with acclaimed LeanPD process models. The LeanKLC framework comprises 23 tasks, each accomplished in one of the seven key stages, these being: knowledge identification, previous knowledge capture, knowledge representation, knowledge sharing, knowledge integration, knowledge use and provision and dynamic knowledge capture.

The rigorous research methodology employed to develop the LeanKLC framework entailed extensive data collection starting with a literature review to highlight the gap in the current body of knowledge. Additionally, industrial field research provides empirical evidence on the current industrial perspectives and challenges in managing product development knowledge. This research was part of a European FP7 project entitled Lean Product and Process Development (LeanPPD), which provided the opportunity to involve industrial collaborators in action research to support practical aspects during the LeanKLC framework development.

The synthesis with the current LeanPD paradigm is accomplished by demonstrating the LeanKLC stages in two distinct streams related to the development of A3 thinking for problem solving and the development of trade-off curves to facilitate set based design at the conceptual stage. The novel LeanKLC is validated in two case studies providing the industry with detailed insights on real product development applications. In particular this research highlights that the LeanPD knowledge environment is a wide subject area that has not yet been thoroughly understood and that industry engagement in empirical research is vital in order to realise any form of LeanPD transformation.

Keywords: Three Dimensions of Knowledge Management, Lean Product Development, Knowledge Life Cycle, A3 Thinking, Trade-Off Curve

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Most of the work presented is carried out in scope of the LeanPPD project and therefore the author wishes to recognize the European Commission for its funding, as well as the research partners for their mainly pleasant collaboration in accomplishing the challenging deliverables. The author also wants to thank industrial partners who supported the practical aspects of the research, in particular Paul Ewers, Howard Roberts, Mark Stubberfield and Martin Molyneaux at Visteon Engineering Services, Robert Sulowski at Sitech, Dr Frank von Lacroix, Dr Wolfgang Geisler and Robert Furian at Volkswagen Group, and Dr Badr Haque and Dave Lowe at Rolls Royce.

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"The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of a planter, for the future. His duty is to lay the foundation of those who are to come and point the way" (Tesla, 1934).

To my parents, Jovan and Mira

За моје родитеље, Јован и Мира

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LIST OF ABBREVIATIONS

3D	Three Dimensions
A3	Problem Solving Technique on one Size of A3 Paper
A3LAMDA	As above based on LAMDA
BOM	Bill of Materials
CAD	Computer Aided Design
CE	Conducted Emissions
CI	Conducted Immunity
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
KBE	Knowledge Based Engineering
KLC	Knowledge Life Cycle
KM	Knowledge Management
LAMDA	Look Ask Model Discuss Act, Product Development Learning Cycle
LeanKLC	Lean Knowledge Life Cycle
LeanPD	Lean Product Development
LeanPPD	Lean Product and Process Development
OEM	Original Equipment Manufacturer
PD	Product Development
PDCA	Plan Do Check Act, Continuous Improvement Cycle
PDM	Product Data Management
PDP	Product Development Process
PLM	Product Life-cycle Management
RE	Radiated Emission
RI	Radiated Immunity
RR	Rolls Royce
SBCE	Set-Based Concurrent Engineering
VES	Visteon Engineering Services
VW	Volkswagen

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Chapter 1

INTRODUCTION

1.1 Research Context

The significance of knowledge is widely acknowledged throughout the corporate environment. Companies constantly seek ways of increasing their knowledge base in order to guarantee long term success and sustainability in a highly competitive and global environment. For manufacturing companies this applies mainly in the development of new products by re-using knowledge created from previous projects and representing it in the form of a new design. Consequently, Knowledge Management (KM) was established as a discipline to empower companies, with supporting tools, templates, technologies, principles, methods, models, theories and philosophies by addressing key stages of the Knowledge Life Cycle (KLC).

However, companies and academics found difficulties in embedding knowledge management in all aspects of the product life cycle, especially in product development, which evidence will be presented in Sections 3.6 and 4.4. Hence, knowledge management was mainly applied as a philosophy at high corporate level. Also, Knowledge Based Engineering (KBE), a specific application of knowledge management, was mainly found in isolated domain specific and case study applications. Nevertheless, manufacturing companies acquired many advantages in adopting several associated technologies such as knowledge based or expert systems, knowledge repositories and embedding design rules in the computer aided design system. Also, improvements in product data and product lifecycle management technologies helped companies to handle the continually increasing amounts of data and information during product development.

The research context of this thesis comprises an interlink between three main research areas, namely traditional product development, Lean Product Development (LeanPD) and knowledge life cycles, as shown in Figure 1.1. Traditional product development was used since the commencement of the industrial revolution, when companies needed for the first time to develop new products for a particular market. Its complexity evolved over the years when products became more sophisticated as a result of increased customer demand, meaning that new products needed to be developed with different functions, phases and activities in a concurrent way (Ulrich and Eppinger, 2008). However, the main principle remained the same, during the concept phase one design solution was chosen and considered throughout the entire product development process.

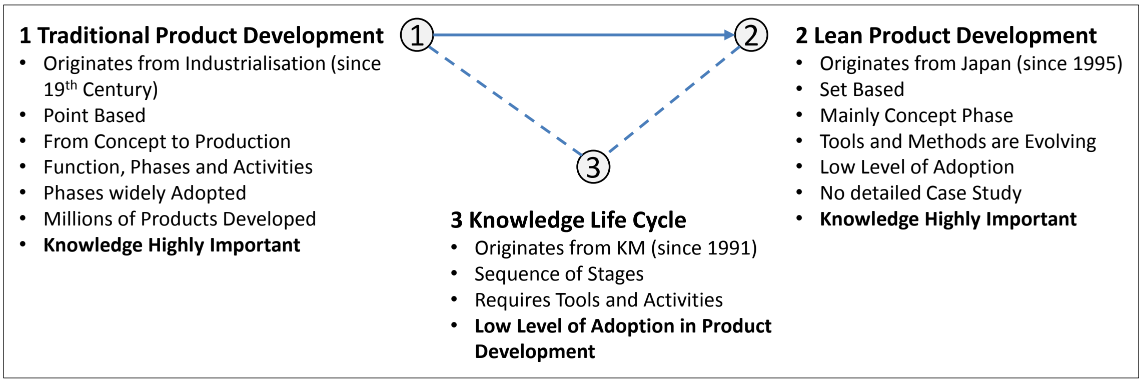


Figure 1.1 Research Context

In 1995, the lean product development community comprising Ward et al. (1995) alternatively introduced a set based concurrent engineering process, meaning that multiple design solutions are considered and narrowed down as the product development proceeds until the optimum design solution is found. Nevertheless, lean product development is still a very conceptual idea, with no detailed tools or methodologies available and no detailed level of implementation. This was the main initiator for the formation of the parent project of this research, entitled Lean Product and Process Development (LeanPPD), which will be explained in Section 1.4.

Traditional product development on the other hand, revealed during this research as widely adopted and understood among manufacturing companies ever since its introduction. Both approaches, traditional and lean product development, obligate a common agreement that knowledge is highly important. In particular, the lean product development community is discussing certain elements of a knowledge environment. However, a thorough consideration of knowledge life cycle activities was not addressed entirely by any of the product development processes. Knowledge life cycles originate from the KM discipline and are also associated with knowledge management frameworks, describing the stages, activities and tools required to capture, create and re-use knowledge. In this context, this research is addressing the required lean knowledge life cycle necessary to effectively manage knowledge in a lean product development environment.

1.2 Research Motivation

The shape of new product designs is becoming increasingly sophisticated with each new generation, resulting in more complex product development processes and activities. Therefore, it is difficult for engineers to apply the latest corporate knowledge during product design and development. In addition, factors such as lack of resources, short time to market and changing customer requirements are restricting the engineer's creative nature and ability to use proven knowledge efficiently. Failing to apply proven knowledge will result in non-value adding activities such as design rework having huge implications on the product development performance.

In order to justify the statements above, Section 4.4 will provide evidence of 38 industrial challenges faced by designers and engineers in managing product development knowledge. Motivated by the large number of challenges faced by the industry, a framework was envisioned to facilitate the adoption of knowledge life cycle activities and support decision taking, particularly during product development. Another motivation arises as the lean product development community finds more acceptance in industry and academia to align the framework with key elements of lean product development and support its implementation.

1.3 Research Aim and Objectives

The aim of the research is to develop a Lean Knowledge Life Cycle (LeanKLC) that will guide manufacturing companies towards the transformation into a knowledge environment and support LeanPD implementation.

This research comprises four research objectives, which are to:

a) Synthesise the role of a knowledge environment in lean product development through a literature review and industrial applications;

b) Understand future key stakeholders by capturing Industrial challenges in managing product development knowledge;

c) Develop a LeanKLC framework to support LeanPD applications;

d) Validate the LeanKLC through industrial case studies.

1.4 LeanPPD –EU-FP 7 Project

This research was part of a European FP7 project entitled Lean Product and Process Development (LeanPPD). The LeanPPD project aims to address *the needs of European manufacturing companies for a new model that goes beyond lean manufacturing, to ensure the transformation of the enterprise into lean environment* (Al-Ashaab et al.,2010).

The LeanPPD model (Al-Ashaab et al.,2010), shown in Figure 1.2, was the conceptual idea that comprised the main enablers of value focus, set based concurrent engineering as the underlying process, knowledge based engineering and knowledge based environment to support engineering decision taking based on proven knowledge and experience. Also a set based lean design tool was envisioned to support the narrowing down of different design solutions during set based concurrent engineering. As shown in Figure 1.2, the consideration of multiple sets would enhance the product development value stream as well as create new knowledge.

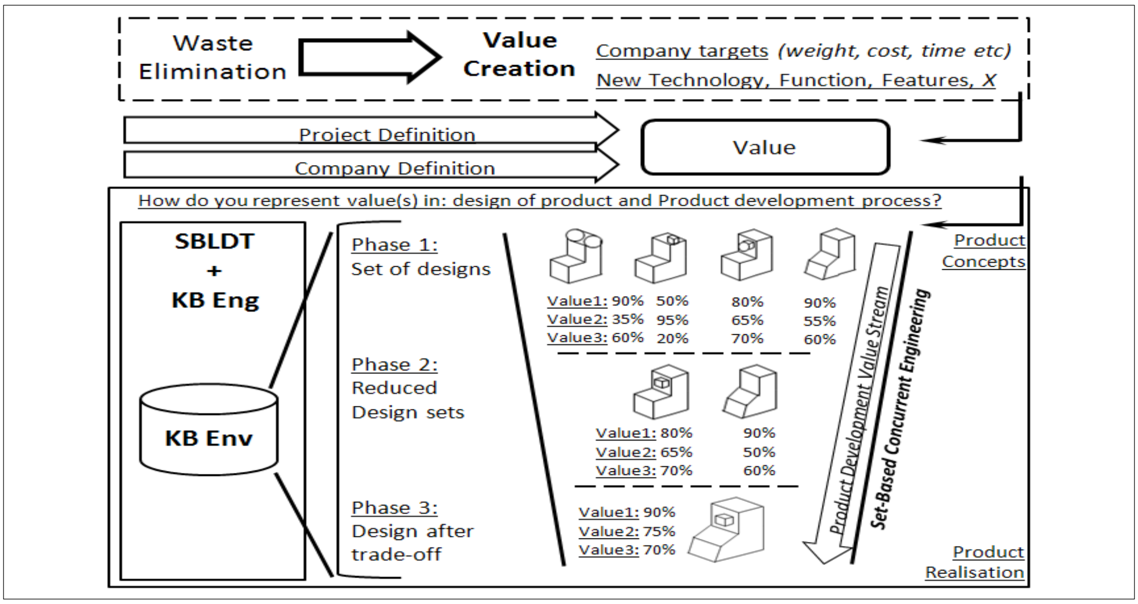


Figure 1.2 Conceptual LeanPPD Model (Al-Ashaab et al. 2010)

The entire LeanPPD project consisted of several other enablers; such an assessment tool and product development value mapping tool, which were developed in different work packages in line with research and industrial collaborators across Europe. The research collaborators were the Institute for Applied Systems Technology Bremen, Ecole Polytechnique Fédérale de Lausanne, Fundación Labein Tecnalia and Sisteplant in Bilbao, Politecnico di Milano, Warwick Univeristy and Cranfield University. The details of industrial collaborators with the LeanPPD project primarily involved in this research are explained in the following section.

1.5 Industrial Collaborators of the LeanPPD Project involved in Research

The presence of five industrial partners in the LeanPPD project gave the opportunity to undertake an industry driven research. However initial data collection in form of industrial requirements gathering and field study, which will be presented in Sections 4.2 and 4.3, revealed different levels of interest in the work presented research among the industrial partners. For this reason the close collaboration necessary as part of the action research was primarily undertaken in four companies, namely Visteon, Rolls Royce, Volkswagen and Sitech.

Visteon Engineering Services is a leading provider of climate, electronics, interiors and lighting product lines for global vehicle manufacturers. The company employs approximately 22,000 people over 120 facilities in 28 countries. Visteon Engineering Services in Chelmsford, UK represents one of the four global technical centres for electronic products (Visteon, 2013). Visteon was involved in adopting a number of key concepts in this research to support decision taking in product development. Hence, the collaboration with Visteon supported several practical aspects during LeanKLC framework development and included the definition and supervision of two master thesis projects (Zhu, 2011; Alhuthlul, 2011) in related subject areas.

Rolls-Royce Holding plc develops and manufactures integrated power systems for civil aerospace, defence aerospace, marine and energy applications. In 2012 the company employed over 40,000 people in over 50 countries worldwide. Rolls-Royce established a prime reputation in its operating sectors to such an extent that the order book at the end of 2012 was equal to five years of operating revenue (Rolls-Royce, 2013). The collaboration with Rolls Royce for this research was mainly of a knowledge exchange nature. Several industrial workshops were organised to exchange knowledge between academia and industry as Rolls Royce has a remarkable reputation and core competences in the related field of knowledge management. Also the researcher contributed and co-authored research related to semantic knowledge life cycle approaches for aerospace design engineering (Sanya et al.,2011) in Rolls Royce.

Volkswagen group is the largest carmaker in Europe with a representative world market share of over 12% for passenger vehicles in 2011. The group comprises 12 brands from 7 seven European countries such as Volkswagen, Audi, Skoda, Seat and Porsche and employs over 500,000 people in 100 manufacturing sites worldwide (Volkswagen, 2013). Volkswagen adapted several elements of this research through an internal initiative including industrial requirements for a knowledge-based software environment in the design process (Furian et al., 2011) as well as knowledge management to support set based product development (Furian et al., 2012).

SiTech develops and manufactures vehicle seats with production sites in Poland, Germany, and China. The company is a 100% subsidiary of the Volkswagen group and employs approximately 4,500 people. Manufactured seat assemblies or seat structures are delivered to automotive OEM sites located in four continents around the globe (Sitech, 2013). In Sitech the researcher was able to guide the adoption of a number of lean knowledge life cycle stages in the form of three thesis projects (Cuenca Tamarit, 2010; Lamacchia, 2010; Herran Mungia, 2011) undertaken by master students as well as the development of a knowledge based engineering prototype (Sorli et al., 2012) as part of a LeanPPD deliverable. Moreover, the collaboration with Sitech enabled the researcher to develop a novel concept for knowledge visualisation in product development using trade-off curves (Maksimovic et al., 2012).

In addition to the above presented main industrial collaborators, interaction with other companies occurred via different settings, such as during two LeanPPD industrial workshops and during the industrial field study, of which the latter is presented in Section 4.3.

1.6 Thesis Structure

This thesis comprises seven chapters aligned in sequential order of the research as illustrated in Figure 1.3. Chapter 2 describes the methodology adapted to undertake this research. Chapter 3 reviews the literature related to knowledge life cycles and lean product development. In addition it reviews previous research in identifying challenges in managing product development knowledge.

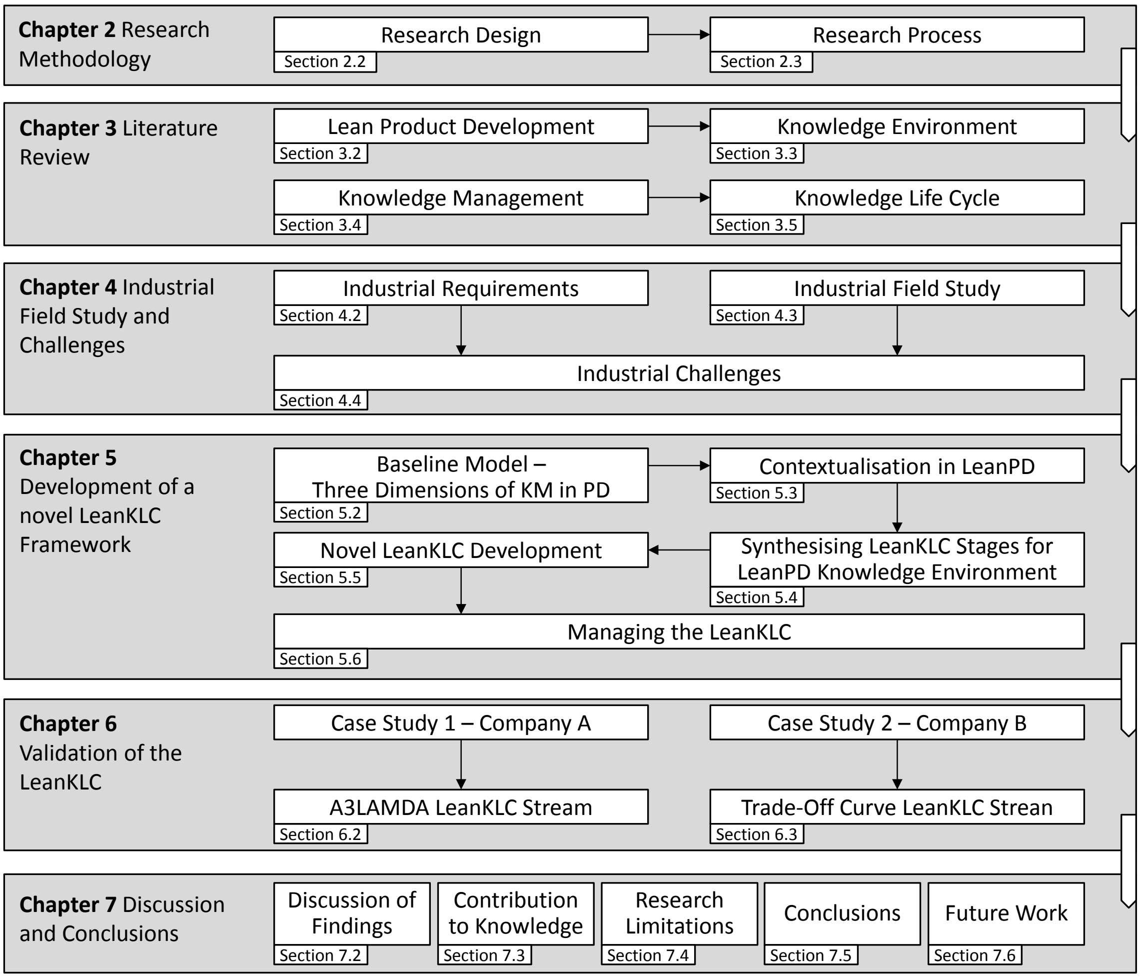


Figure 1.3 Overview of Thesis Structure

Chapter 4 presents the industrial perspectives and challenges, including industrial requirements gathering, field study and challenges classification. Chapter 5 describes the development of the LeanKLC as a major contribution of the work presented research. This includes as shown in Figure 1.3, a baseline model and its contextualisation with current LeanPD perspectives, followed by the explanation of the novel LeanKLC framework, entailing stages, tasks and techniques. Chapter 6 describes the industrial application and validation of the LeanKLC in two case studies. Chapter 7 discusses the research findings and outlines the contribution to knowledge and research limitations as well as the conclusion and future work.

1.7 Chapter Summary

This chapter presented the context, motivation, aim and objectives in order to familiarise the reader with the research to follow in this thesis. In addition it provided details of the parent project, entitled LeanPPD, in which the researcher contributed to several deliverables in the research related topics. More importantly, the LeanPPD project provided the opportunity to involve several industrial partners in empirical research. The detailed explanation of the employed research methodology is explained in the following chapter.

Chapter 2

RESEARCH METHODOLOGY

2.1 Introduction

This chapter describes the methodology followed by the author in order to conduct the research. As shown Figure 2.1 the research methodology as a systematic approach consists of a research design, Section 2.2, and research process, Section 2.3. The former positions the type of research as well as depicting adequate research strategy and methods.

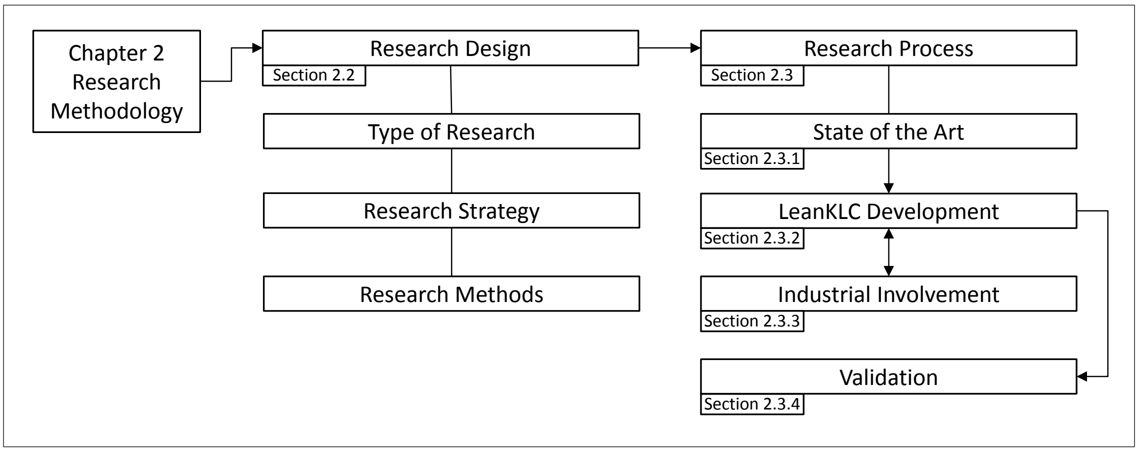


Figure 2.1 Scope of Chapter 2

The research process on the other hand provides the overall phases needed to complete the research alongside its anticipated output. The research phases include state of the art, lean knowledge life cycle (LeanKLC) development, industrial involvement and validation.

2.2 Research Design

Research is a systematic process, using scientific methods, to discover or investigate new facts. Its methodological approach is mainly manifested by ontology, in particular how the researcher interprets the reality (Holosko and Thyer, 2011). The practical reality of this research document comprises the development of a framework that organisations adopt to improve product development performance. Subsequently, it requires the active participation of human beings as its key stakeholders, namely product designers and engineers. As such, the ontology of this research is based on real world settings of which stakeholders are interdependent social actors and therefore its assumption applies to the realistic view (Huff, 2009) or constructivism (Bryman and Bell, 2007). Henceforth, according to the author's interpretation, this research is situated most appropriately in social research devoted to organisational studies (Bryman, 1989) along with real world research as popularised by Robson (2011).

The research design is particularised by defining a type of research, strategy and its methods for data collection, as shown in Figure 2.2. Three main research types of research design are largely applied by academic scholars, namely qualitative, quantitative and mixed design (Burns, 2000; Creswell, 2009; Huff, 2009; Robson, 2011). Quantitative research is suitable for research that encompasses a hypothesis, prediction, testing as well as generalisation to a subject (Huff, 2009). The researcher is mainly engaged in statistical analysis and interpretation using numerical methods of pre-determined data (Creswell, 2009). Its ideals comprise objectivity, replicable procedures, abstraction and verifiability, although does invite criticism relating to oversimplification as well as misjudged partial definition and procedures (Huff, 2009).

Qualitative research on the other hand, prioritises the viewpoint of those being studied, as the main difference to quantitative (Bryman, 1989). Its nature supports research related to detail explanation, exploration or empathy. Ideals of qualitative research entail rich description, meaning, reflection and connection to the investigated subject area. However, criticism includes subjectivity in the first place as well as weak observations covered as explicit interpretation (Huff, 2009).

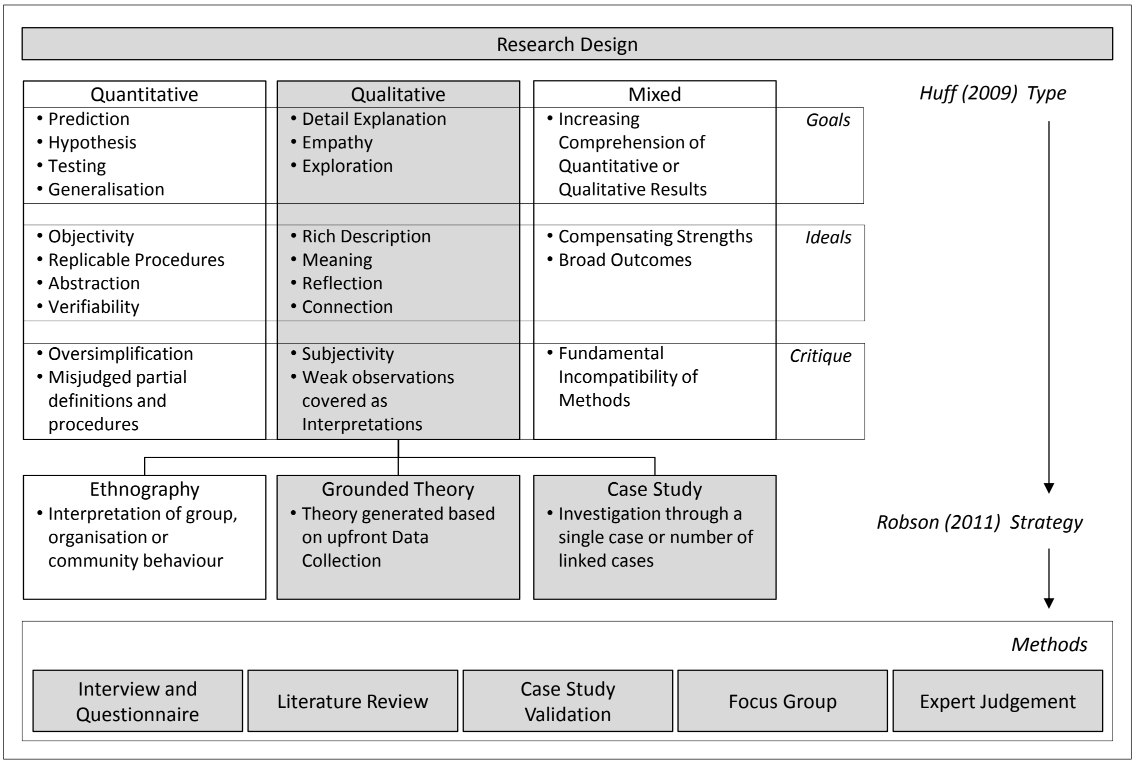


Figure 2.2 Research Design

The third type of research considers a design in which both qualitative and quantitative research are combined in order to increase comprehensive vice-versa. It aims to utilise the strengths of both types to realise a broad outcome. However, there is a significant drawback if a fundamental incompatibility of methods is implied in the area of research (Huff, 2009).

This research document positions itself in qualitative research due to two main reasons. Firstly, product development knowledge is largely dependent on tacit knowledge (Goffin and Koners, 2011, Goffin et al. 2010) hence not providing a substantial ground for objectivity or verifiability on behalf of quantitative judgement. In addition, the author believes that a rationale for using mixed design would lack substantial comparability between quantitative abstraction and qualitative rich description. Secondly, the focus on empathy in essence to understand the participants 'state of mind' (Holosko and Thyer, 2011) is regarded as a key factor to practically synthesise two disciplines, namely knowledge management and lean product development, as investigated during this research.

Given the above, Robson (2011) suggests three main strategies for qualitative research comprising ethnography, grounded theory and case study. Ethnography emphasises studying behaviour of individual, groups or communities (Robson, 2011) in order to gain interpretation of meanings, values and views (Holosko and Thyer, 2011). Ground theory on the other hand relies on initial empirical data collection based on existing theory to interpret its relation and is often used for inductive theorising (Huff, 2009). Case study, as a third and final research strategy, comprises the investigation of a theory based on a single case study or number or linked case studies of an individual or group of participants (Robson, 2011). This research adapts the strategies of ground theory and case study for the following reasons.

In order to address research objective b), which is the capturing of Industrial challenges in managing product development knowledge, as presented in Section 1.3, ground theory is seen as adequate to interpret basic principles in knowledge management as against empirical first hand data collection. In addition, such increased understanding subsequently supports research objective c), relating to the development of a LeanKLC framework and so strengthen its practical justification. Consequently, validation as part of objective d) is considered using case studies in order to determine practical implications of key principles developed during this research.

The selection of methods for data collection is shown in Figure 2.2 and comprises questionnaire, interview, literature review, case study validation, focus group and expert judgement, of which supporting tasks as part of the research process are presented as follows.

2.3 Research Process

After identifying research type and strategy the research process presents the phases, tasks and methods adapted as well as its resulting output. As shown in Figure 2.3, the adapted research process comprises four phases, namely state of the art, LeanKLC development, industrial involvement and validation. Each phase consists of several tasks for accomplishment using a total of six methods for data collection. These are literature review to establish a research gap, interview and questionnaire to obtain industrial perspectives, focus group to carry out industrial application and finally case study validation and expert judgement to derive a conclusion from the research.

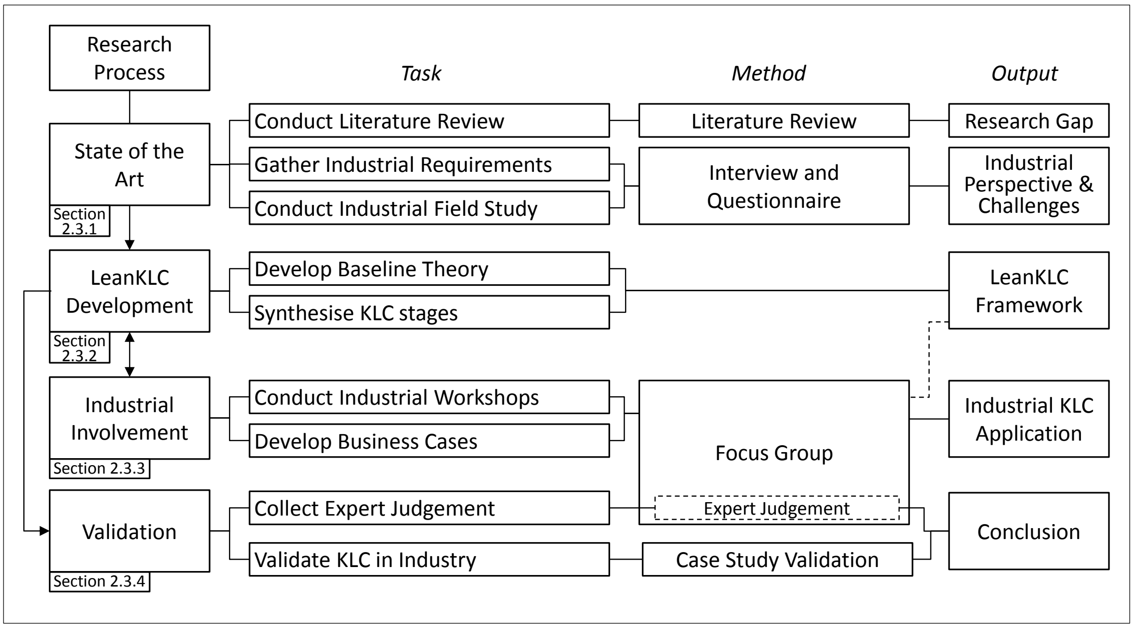


Figure 2.3 The Process in the adapted Research Methodology

The sequence of research phases is complex and interrelated. Industrial involvement supports the LeanKLC development and vice versa supported by action research. The collection of expert judgement data for validation is undertaken in focus groups, a method which is also used in for the industrial involvement phase. Hence, the research phases as well as rationale and detail of the chosen methods is explained as follows.

2.3.1 State of the Art

In this phase the state of the art in the literature as well as in current industrial knowledge life cycle applications is explored. The latter includes gathering of industrial requirements for a knowledge based architecture and environment, and an industrial field study aiming at analysing current industrial practices with regards to knowledge capture, re-use and creation. As a result of first hand data collection, also including narrative data, the classification of industrial challenges was accomplished as an additional task. The phase of state of the art was undertaken using three methods for data collection, namely literature review, interviews and questionnaires.

2.3.1.1 Literature Review

This method reviews the existing knowledge as published in academic literature, in other words the secondary research. According to Huff (2009) it provides the conversational exchange, back and forth, among empirical and theoretical arguments. Its outcome is the research gap, providing guidance for knowledge contribution

(Robson, 2011), as will be presented in Section 3.7 for this research. As such, a keyword search alongside alerts was used to establish a systematic and on-going strategy due to two main reasons. Firstly, using keyword search to review the state of the art was previously deployed by Tjahjono et al. (2010) for six sigma and Baines et al. (2006) for lean design engineering and regarded as an effective method to find an initial set of relevant papers as well as assessing the response to a related topic.

Secondly, synthesising three elements of the research context, as illustrated in Figure 1.1, required a sequence to retrieve interrelated publications. Hence, search included knowledge management related keywords including ‘knowledge sharing’ and ‘knowledge representation’ as well as interdisciplinary keywords such as ‘knowledge AND lean’. Figure 2.4 illustrates the extent of the keywords used in this research. The keyword search was performed in four academic databases, namely Scopus, Emerald, Springer Link and Google scholar using four different search configurations to filter the most relevant papers and overcome overload of search results.

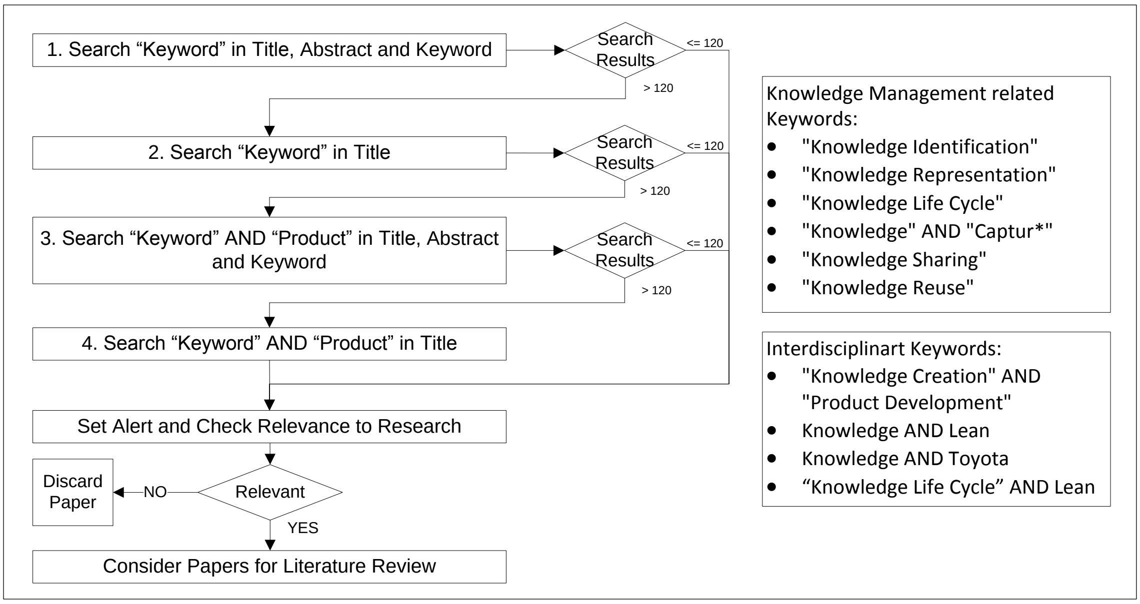


Figure 2.4 Literature Review Keyword Search Flow-Chart

As shown in Figure 2.4, the first configuration searched keyword within “Title, Abstract, Keyword” in the database. If fewer than 120 results were found then results were checked for relevance. However, if more than 120 results appeared the search continued with search configuration 2, where the keyword was only searched in the “Title”, as shown in Figure 2.4. The threshold of 120 results was chosen by the researcher as it represents an approximate amount of paper found in comparable PhD theses. The search continued until fewer than 120 results were found or until the search reached configuration 4. In configurations 3 and 4 the word "Product" was added to additionally filter the keyword search within related disciplines of "Product" -lifecycle, -design, and -development. The resulting literature review is presented in Chapter 3.

2.3.1.2 Interviews and Questionnaire

The data collection through interviews and questionnaire are explained in this section in combination due to the apparent relationship as illustrated in Figure 2.5. Interviews are categorised by Robson (2011) into three types, structured, semi structured and unstructured. Unstructured interviews are informal settings although the interviewer has a general area of interest in which conversation develops accordingly. During semi structured interviews the interviewer is guided by an initial set of questions in which wording can be adjusted according to the evolving conversation. Structured interviews on the other hand are rigid in the wording of questions as well as sequence and to the same for every participant (Robson, 2011).

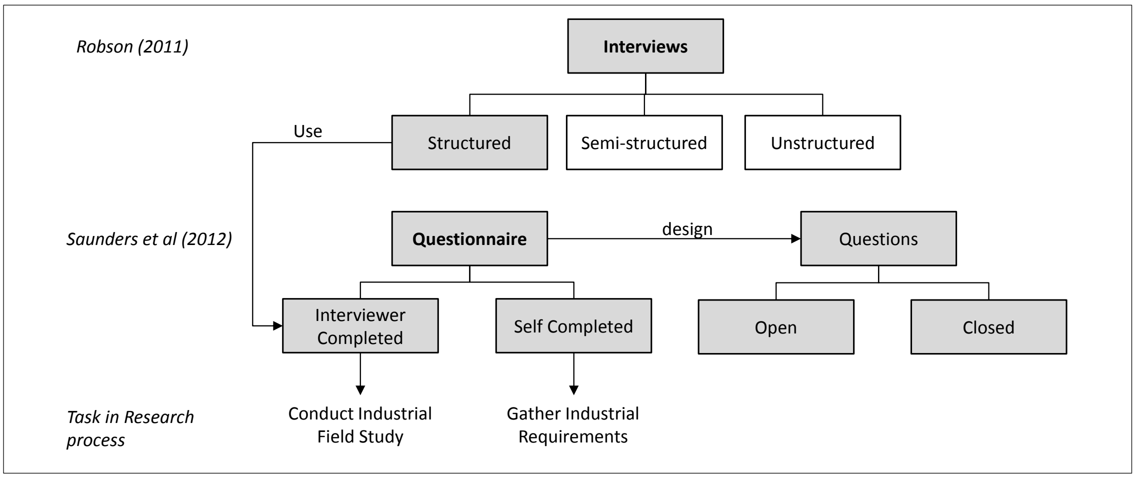


Figure 2.5 Data Collection via Interviews and Questionnaire

As illustrated in Figure 2.5, Saunders et al. (2012) suggest the use of questionnaires during structured interviews which is referred to as interviewer completed or administered questionnaire. The second type of questionnaire is self-completed or administered, which requires the participant to complete independently. The design of questions is based on open and closed questions. Open questions are helpful for collecting a broad range of opinion whereby closed questions are used to gather attitudes on given choices or Likert scale for a particular subject (Saunders et al., 2012).

In this research structured face-to-face interviews using open and closed questions were adapted for data collection during the field study due to the following. Face to face interviews as well as interviewer administered questionnaires gave the opportunity to provide a basic understanding of knowledge management key principles to the engineers upfront and during data collection in order to reduce interview bias. In addition to closed questions, the use of open questions enabled the engineers to express empathy although within a particular subject area. The use of structured interviews on the other hand focused on a particular subject area with regards to knowledge life cycle applications, which context was clearly established for this research.

The gathering of industrial requirements as another task comprised the use of self-administered questionnaires in which engineers rated relevance and feasibility to the implementing of functional requirement via closed questions but also to express related key concerns via a set of open questions. The use of self-administered questionnaires was chosen as it gave participants time to investigate the questionnaire internally in order to provide adequate feedback. In order to avoid questionnaire bias the author provided an explanatory presentation to each participant before completion.

Alongside the above mentioned interviews, the researcher has captured the interview data using hand written notes as well as voice records. This resulted in narrative data of which the researcher was able to classify key concerns in the form of industrial challenges as presented in Section 4.4. Narrative data is defined by Holosko and Thyer (2011) as a key source for qualitative research and hence provided major guidance for the development of the LeanKLC of which the research phase is explained as follows.

2.3.2 LeanKLC Development

In this phase the researcher develops the LeanKLC supported by a baseline theory in order to increase understanding for future stakeholders. In addition, the synthesising of LeanKLC stages comprises definition of sequential stages, including tasks and techniques. Both the aforementioned contribute to the output of the resulting LeanKLC accomplished via action research and are explained as follows.

2.3.2.1 Action Research

Action research is largely popularised by Pasmore and Friedlander's (1982) methodological approach to solving a problem related to the large number of injuries during the manufacture of electronic products. It comprises direct investigation as well as collaboration between researcher and client in order to discover a diagnosis and elaborate recommendations as well as evaluate solutions to a problem in order to contribute empirical knowledge (Bryman, 1989).

Action research presents one of the essential methodologies in qualitative research (Holosko and Thyer, 2011) and found recent recommendation in a comprehensive application of lean product development principles accomplished by Liker and Morgan (2011) at the Ford Motor Company. Liker and Morgan (2011) clearly state with regards to future work that *"for the specific case of lean product development, the most valuable methodology is action research that elucidates ways to approach key issues such as culture change, standardisation and innovation, front-end loading and innovation, use of requirements engineering and use of obeya."* Learning from such experience, the author decided to additionally use action research for the LeanKLC development, the adaption of which is presented in Figure 2.6.

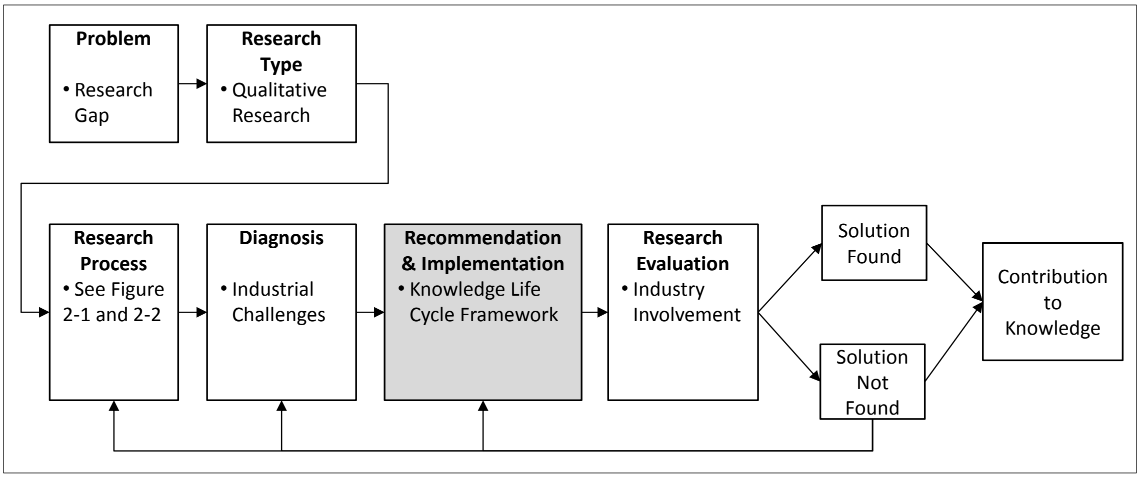


Figure 2.6 Stages of Action Research adapted from Brynan (1989)

The LeanKLC development comprises the recommendation and implementation as the centric stage of action research as shown in Figure 2.6. Its development is directed by stages of problem definition, research type, research process and diagnosis. The repetitive loop between research evaluation through industry involvement and instance of solution not found provided a major source of data collection in order to feed back to the previous stages. For example, diagnosis in the form of industrial challenges was an on-going process until a robust definition was concluded. Henceforth this gave the opportunity for the industrial partners to express key concerns and improvement suggestions in relation to the development of the LeanKLC as a key advantage of this research method.

2.3.3 Industrial Involvement

The phase of industrial involvement comprises two tasks, namely conduct industrial workshops and develop business cases. Its main purpose is to involve industrial partners in action research which in return requires data collection. In addition this phase actively develops potential business cases for applying the developed framework. The research method used is focus group and is explained as follows.

2.3.3.1 Focus Group

This research method is associated with the term of group interview (Robson, 2011) in which participants extensively share opinion and experience on a particular subject (Morgan, 1997). This on the other hand, is subject to dynamic group behaviour (Brod et al., 2009) which in return demands the researcher to host as well as steer a debate with regards to the research focus. For these reasons focus groups were undertaken in the form of industrial workshops at the participant's company sites. The industrial workshops were conducted in a structured manner to establish an active interaction between the researchers and the participants. This gave the opportunity to the latter to express their key concerns arising from their daily activities in product design and development. The industrial workshops were designed to showcase potential tools and methods that the designers and engineers could use to improve the management of their product development knowledge.

In addition, several focus groups have been conducted in order to obtain expert judgement which is seen as important to reduce bias (Inglis, 2008), increase content validity (Joo and Lee, 2011) as well as providing opportunity for experts to express tacit knowledge (Benoit and Wiesehomeier, 2009). As such, expert judgement provided direction related to transferability of the work presented research among different organisations by adapting triangulation, a technique used in qualitative social research to establish credibility (Holosko and Thyer, 2011).

2.3.4 Validation

Validation represents the final phase of the research process and comprises the conduct of industrial case studies, explained as follows.

2.3.4.1 Case Study Validation

In Section 2.2, Figure 2.2 presented the research strategy comprising grounded theory and case study for this research. Previous data collection was mainly concerned to support the former, whereby this section describes the method of case study validation. This form of validation will focus on key concepts of the developed research. Yin (2009) defines four logical tests as criteria for judging the quality of empirical social research; these are construct validity, internal validity, external validity and reliability.

Such tests have implications for the case study tactic as well as design types, taking shape in the form of single-case or multiple-case as well as holistic or embedded design, as shown in Figure 2.7. The source of evidence is collected using methods such as documentation, archival records, interviews, direct observation, participant observation and physical artefacts (Yin, 2009).

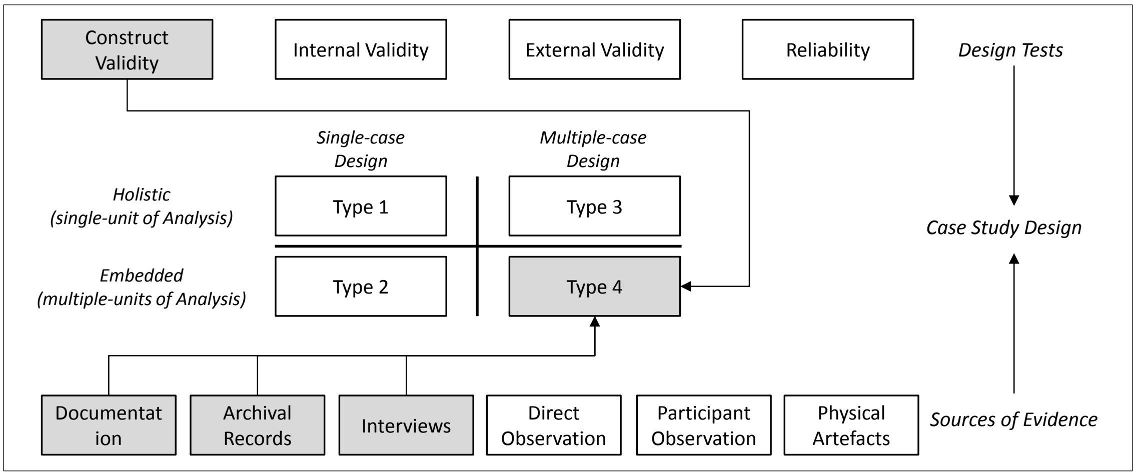


Figure 2.7 Case Study Research - Tests, Design and Source of Evidence from Yin (2009)

The adapted case study validation for this research is construct validity, which according to Yin (2009) involves detecting operational measures of the concepts developed most preferably using multiple sources as well as chain of evidence. As shown in Figure 2.7, construct validity was investigated using embedded multiple case designs. Internal validity was not applicable to this research as it is used in experimental design (Yin, 2009). External validity as well as reliability via case studies on the other hand was not considered due to the diversity of knowledge domains among product development activities. As shown in Figure 2.7 sources of evidence during case study validation included documentation, archival records and interviews.

2.4 Chapter Summary

Chapter Two presented the research methodology in which the author positioned its approach as qualitative research. It also covered the adapted research process which constitutes of phases, tasks, methods and output. A clear focus has been directed to the industrial involvement, in particular the collection of empirical data in order to develop the envisioned LeanKLC via action research. The first phase of the research process is titled state of the art, which the literature review refers to in the following chapter.

Chapter 3

LITERATURE REVIEW

3.1 Introduction

Chapter 3 presents the review of the related literature. The particular scope of the literature review as defined by the author is shown in Figure 3.1 and covers research in lean product development and knowledge management.

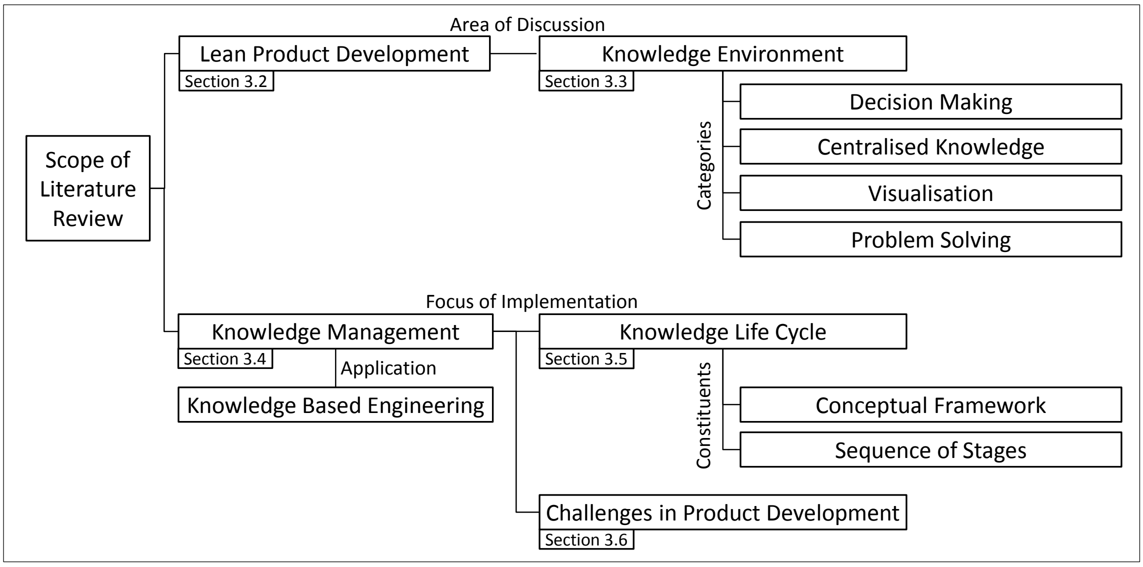


Figure 3.1 Scope of Literature Review

Although lean product development research comprises several areas of discussion, this review will focus particularly on the knowledge environment in Sections 3.2 and 3.3, hence it is related to the aim and objectives of the research. During the literature review the author identifies four key categories within the lean product development literature that describe a knowledge environment, namely decision making, centralised knowledge, visualisation and problem solving. The review in the research area of knowledge management focuses on previous research that developed a framework and defined key stages of the knowledge life cycle, in Sections 3.4 and 3.5. The review subsequently covers research in knowledge based engineering, a particular application of knowledge management, because it addresses the representation side and computational use of the knowledge life cycle. In order to provide this research with a broader understanding of some of the implications of previous research, the review also covers the challenges in managing product development knowledge in Section 3.6.

The literature review was supported by a keyword search strategy as part of the research methodology, presented in Section 2.2. The keyword search strategy resulted in over 1,400 suggested publications, though still containing non related or low profile studies as well as duplicate search results from the different academic databases. Consequently, 169 publications have been selected that were considered by the author as adequate to represent the research related literature review. Figure 3.2 illustrates the number of publications reviewed for each year of publication as well as the difference of those related to knowledge management and lean product development.

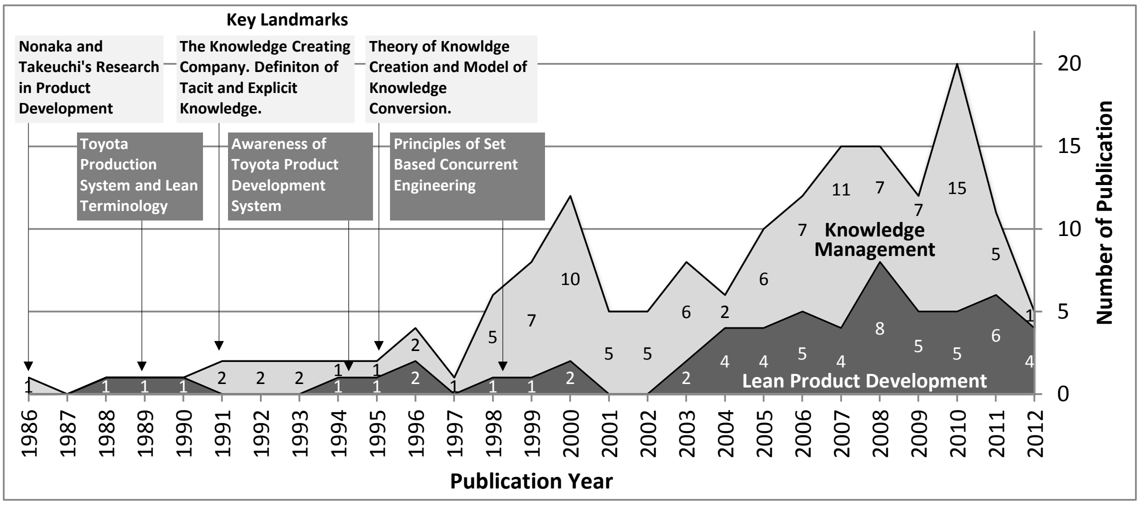


Figure 3.2 Numbers of Publications reviewed compared to Publication Year

The number of publications identified and reviewed in lean product development (58) compared to knowledge management (111) is significantly lower, indicating that its research has been addressed by a smaller community. Figure 3.2 also illustrates the key landmarks that ignited these two highly valued research areas. The detail of the key landmarks and state of the art are presented in the following sections.

3.2 Lean Product Development

The terminology of lean was established by Womack et al. (1990) and largely manifested through Womack and Jones' (1996) lean thinking paradigm emphasising waste elimination, value creation and continuous improvement. It was derived from the Toyota production system which was intended to establish a simple and repeatable manufacturing pattern for the 20th century (Ohno, 1988; Shingo, 1988). As a result, lean manufacturing found an immense acceptance in the production environment (Liker, 2004; Dickmann, 2009).

Research initiatives and understanding on lean product development systems on the other hand, were comparably lower (Liker and Morgan, 2011; Letens et al., 2011) and mainly based on the Toyota product development system (Morgan and Liker, 2006; Kennedy, 2003; Kennedy et al., 2008; Ward, 2007; Sobeket al., 1998). Product development comprises a set of activities to conceptualise, design, test, produce and launch a new product on the market (Ulrich and Eppinger, 2008). Toyota became a benchmark for the majority of the lean product development community even though the company underwent the biggest vehicle recall in automotive history (Liker, 2010) due to product development performance. Khan et al. (2012) identified other approaches to lean product development, such as research adopting concepts of lean manufacturing to product development (Mynott, 2000; Fiore, 2003; 2005; Cooper and Edgett, 2005; Anand and Kodali, 2008; Reinertsen, 2009; Pessoa et al., 2009) or research integrating elements of Toyota product development with lean thinking (Haque and Moore, 2004; Oppenheim et al., 2011; Oppenheim 2004; Hines et al., 2006; Mascitelli, 2006; Schuh et al., 2008). In general, empirical data on lean product development transformation beyond Toyota is limited and has a tendency to oversimplify the natural complexity of product development systems (Letens et al., 2011).

The awareness of the Toyota product development system increased when Ward et al. (1995) introduced set based concurrent engineering, a process which in contrast to the traditional point based product development requires multiple design solutions, outlining how Japanese companies gain advantage in delaying design decisions by relying on sufficient knowledge (Ward, 2007). As illustrated in Figure 3.3, the point based approach limits the design space upfront, hence providing less flexibility to adjust design solutions among the different product development functions. Set based approach on the other hand enables product development functions to explore design space and converge to an optimum design solution during the set narrowing phase (Ward et al., 1995; Liker et al., 1996).

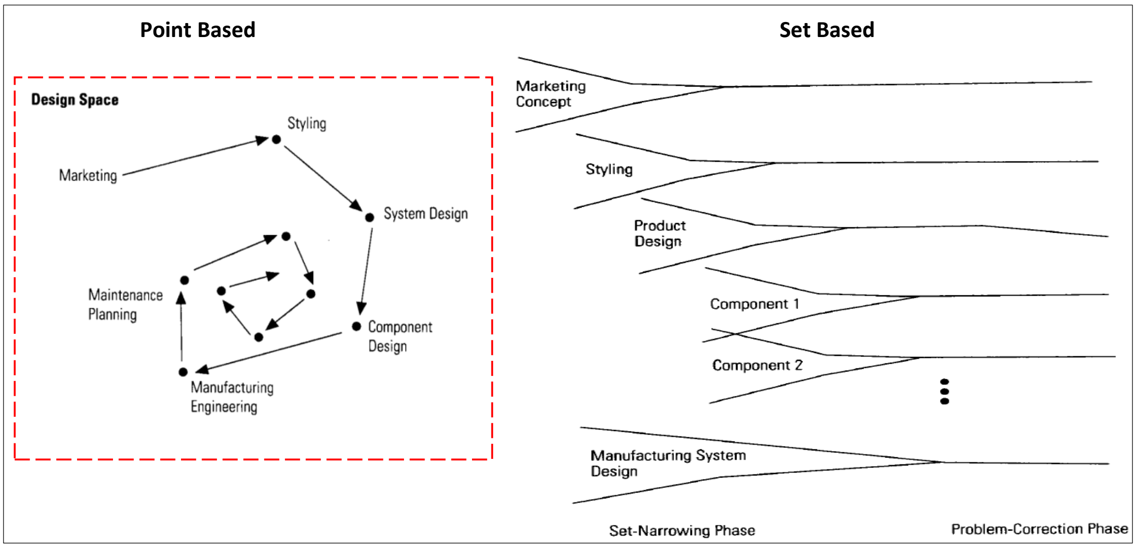


Figure 3.3 Point Based versus Set Based Product Development (Ward et al., 1995)

Set based concurrent engineering is a knowledge intensive process that comprises the communication, trade-off and narrowing down a set of potential design solutions whilst proceeding in product development (Sobek et al., 1999). Moreover, set based concurrent engineering is the underlying process of lean product and process development along with core enablers to support its implementation. As illustrated in Figure 3.4 core enablers of the LeanPPD model include value-focused planning and development, knowledge-based environment, continuous improvement culture and chief engineer technical leadership (Al-Ashaab, 2012).

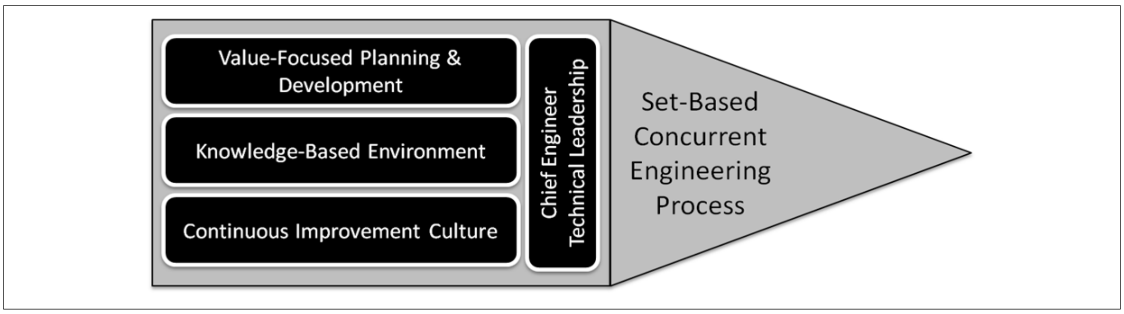


Figure 3.4 Core Enablers of the LeanPPD Model (Al-Ashaab, 2012)

Given the above, the knowledge environment is a core enabler as well as largely discussed area in lean product development literature, as reviewed in the following section.

3.3 Knowledge Environment in Lean Product Development

The knowledge environment discussed in lean product development literature aims to highlight the importance of knowledge from different perspectives. Sobek et al. (1999) for example refers to the cultivating of organizational knowledge. Kennedy et al. (2008) outline the existence of a knowledge value stream that incorporates capture and re-use of knowledge, as an addition to the set based product value stream. Kennedy et al. (2008) and Rooke et al. (2010) use the terminology of lean knowledge management to describe an ambitious condition where companies are able to get the correct knowledge to the right people at the correct time, in the right form and quality.

Ward (2007) on the other hand generalises waste in lean product development as waste of knowledge (Oppenheim et al., 2011). Lindlof et al. (2012) identified that Toyota techniques of mentorship, chief engineer and visualisation have increased potential to support knowledge transfer in lean product development. Hoppmann et al. (2011) defines cross-project knowledge transfer as one of eleven interdependent components in current lean product development literature. Other reviews by Baines et al. (2006) and, Leon and Farris (2011) identified that key elements of knowledge management, such as decision making and knowledge integration, are yet to be thoroughly addressed and standardised to support lean product development.

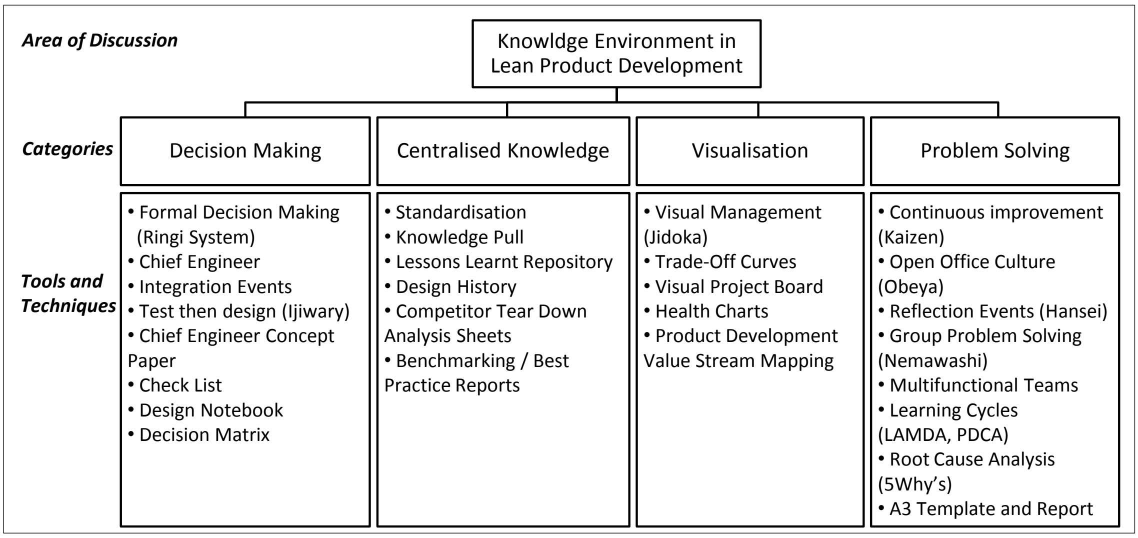


Figure 3.5 Categories, Tools and Techniques of a Knowledge Environment discussed in Lean Product Development Literature

Research in analysing global knowledge management practices at Toyota was undertaken by Ichijo and Kohlbacher (2007; 2008) and Dyer and Nobeoka (2000) though with an increased focus on global knowledge creation strategies and building knowledge sharing networks with suppliers. Given the above, there was no common baseline of discussion found by different researchers to describe a knowledge environment in lean product development. As a result, the author classified tools and techniques discussed in lean product development literature into four main categories to define the knowledge environment, these being decision making, centralised knowledge, visualisation and problem solving. The categories are shown in Figure 3.5 and reviewed as follows.

3.3.1 Decision Making in the LeanPD Knowledge Environment

In Lean product development, decision making is a formal process that incorporates chief engineer and test then design principles supported with tools such as design notebook and chief engineer concept paper (Morgan and Liker, 2006). Integration events in set based concurrent engineering are part of that process to enable engineers to communicate sets and delay decisions to explore alternative solutions (Ward, 2007; Kennedy et al., 2008). As opposed to project managers, a chief engineer is well experienced in technical aspects of product development and supports the design team with proven knowledge in order to trade-off technical solutions (Cousins et al., 2011). Although the role of a chief engineer is of a mentoring rather than managing nature, a chief engineer concept paper ensures that ideas are documented and communicated (Morgan and Liker, 2006). Gautam et al. (2007) reported that product development companies have not established ways to exploit low level knowledge sources such as requirements, functional behaviours and test results. Toyota on the other hand, incorporated the usage of paper based design notebooks which include updated checklists, trade-off curves, decision matrices and design rules which equip the engineer with relevant knowledge to support decision making (Morgan and Liker, 2006).

3.3.2 Centralised Knowledge in the LeanPD Knowledge Environment

Morgan and Liker (2006) outlined that North American companies do not usually efficiently use knowledge databases. Individual departments and functions which would develop their own knowledge databases which decrease the capability of knowledge sharing among cross functional activities. Maintenance of the knowledge database would require huge expertise, so available knowledge was usually incomplete or obsolete. The know-how database at Toyota on the other hand is reported as a seamlessly integrated tool set of active design, simulation and testing to increase the productivity of the design process. The knowledge database is centralised and contains essential information such as design history (Mascitelli, 2006), lessons learnt, competitor tear down and benchmark reports (Morgan and Liker, 2006). It is important to expand the capability for engineers to pull the right knowledge in a preferred form (May, 2010). For example, the use of knowledge databases should not intend to replace the paper based notebooks as previously described; instead it should enhance the search for relevant information and facilitate graphical representations of trade-off values as well as illustrating reasoning behind design rules. One key element in updating centralised knowledge bases is standardisation of related processes and the stored knowledge (Sobek et al., 1999; Morgan and Liker, 2006) though less information on how to achieve it is provided.

3.3.3 Visualisation in the LeanPD Knowledge Environment

At Toyota, Jidoka refers to Visual Management, a technique adapted from lean manufacturing to product development in order to simplify complex knowledge using visual tools (Morgan and Liker, 2006), such as trade-off curves, visual project board (Mascitelli, 2006) and health charts (Liker and Morgan, 2011). Trade-off curves are used to evaluate one design attribute against another (Oosterwal, 2010). They visually display subsystem knowledge in a graph from which engineers explore design space (Ward, 2007) and evaluate design alternatives (Kennedy et al., 2008). Moreover trade-off curves avoid the reinvention of previously considered design solutions during prototyping (Womack, 2006).

However, trade-off curves are also widely used in the area of multi-objective optimization to represent the range of reasonable possibilities on a given criteria (Vassilvitskii and Yannakakis, 2005; Montiel-Nelson et al., 2005). In product development, Roemer and Ahmadi (2004) depict the relationship between overlapping of development stages and crashing of development times. In addition, it is mentioned that companies have the knowledge that can be found in trade-off curves; however, the knowledge can most frequently be found in the engineers' heads. Browning and Eppinger (2002) studied cost and duration trade-offs in an attempt to model the impacts of process architecture on cost and schedule risk in product development.

Another research area is the adoption of value stream mapping to product development, as undertaken by McManus (2005) and Darwish et al. (2010), presenting an adapted tool to visually display product development processes in order to identify and eliminate waste, moreover Liker and Morgan (2011) believe that such a tool is beneficial to understanding critical activities and where knowledge is available.

3.3.4 Problem Solving in the LeanPD Knowledge Environment

Product development is usually described as an ever repeating problem solving activity (Clark and Fujimoto, 1991; Thomke and Fujimoto, 2000; Kalogerakis, 2010; Goffin and Koners, 2011). Ward et al. (1995) for example, describe the second phase of the set-narrowing process as the problem-correction phase. However, problem solving in product development is complex and requires several iterations of problem recognition, alternative generation, evaluation and decision making to determine a solution with sufficient depth of knowledge (Clark and Fujimoto, 1991) as illustrated in Figure 3.6.

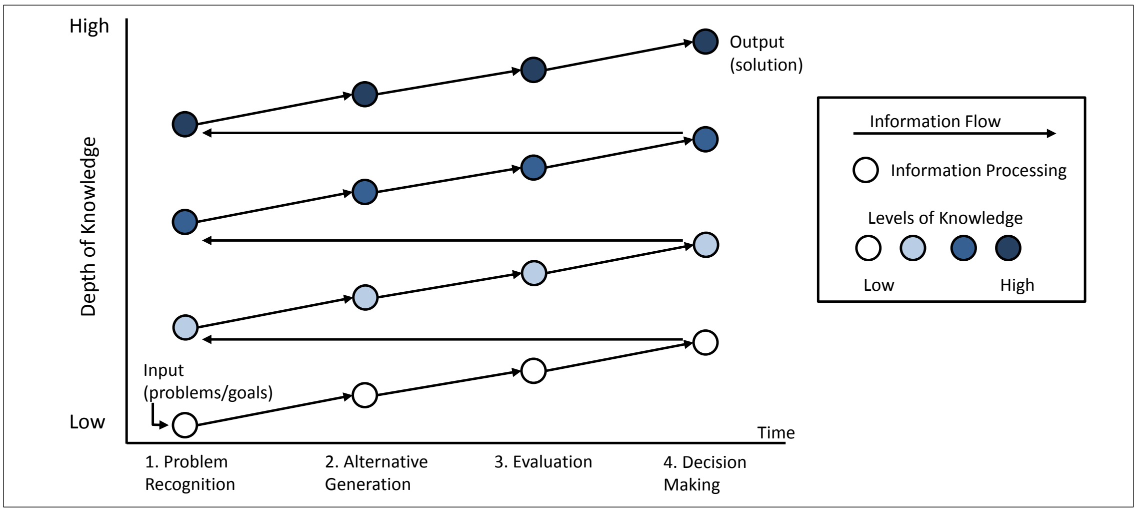


Figure 3.6 Problem Solving Cycle in Product Development (Clark and Fujimoto, 1991)

At Toyota, group problem solving and reflection events are key techniques to solving problems within multifunctional product development teams (Morgan and Liker, 2006; Oosterwal, 2010) as well as within core suppliers (Kamath and Liker, 1994; Kogut, 2000). Open office culture is another technique used to instil group problem solving and sharing of lessons learned in a more informal way (Liker and Morgan, 2011).

The A3 report is based on the Plan Do Check Act (PDCA) continuous improvement cycle and used to solve problems in a structured and simple way on one sheet of A3 sized paper. The traditional A3 template, as illustrated in Figure 3.7, consists of eight elements. The first five elements correspond to the ‘plan’ stage of PDCA and comprise theme, background, current condition, goal and root cause analysis. In particular, the technique of 5Whys facilitates in-depth investigation of root causes. The remaining three elements, counter measures, effect communication and follow-up action correspond to the stages of 'do, check and act', hence closing the loop of the PDCA cycle (Shook, 2008; 2009; Sobek and Smalley, 2008).

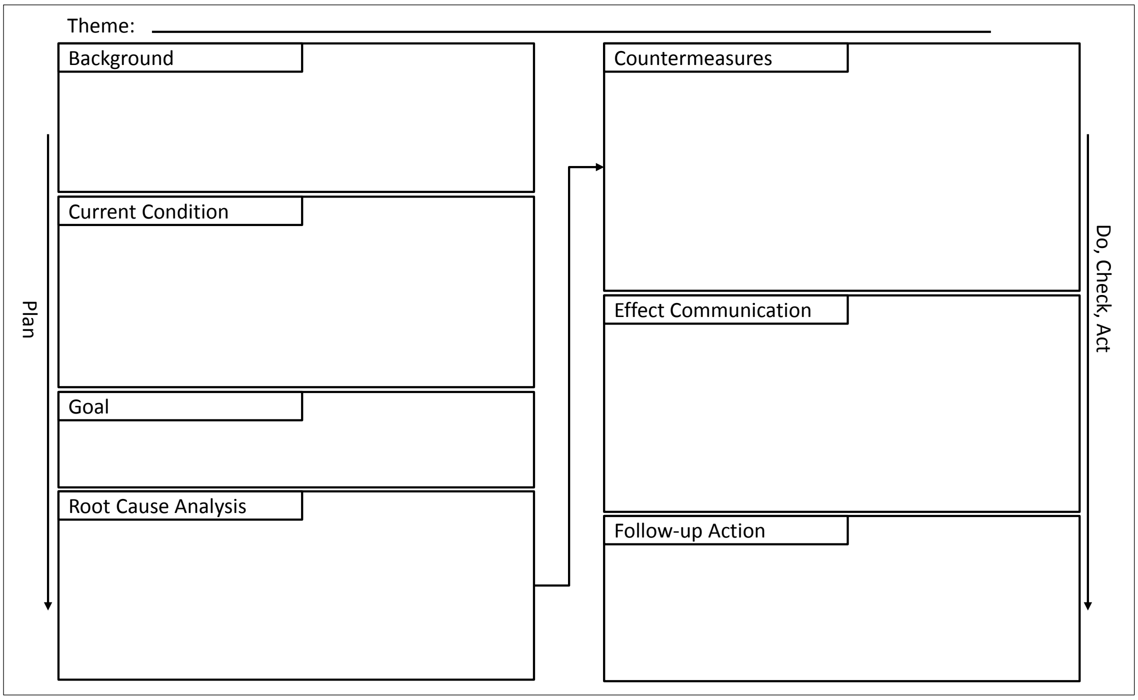


Figure 3.7 A3 Template (Sobek and Smalley, 2008)

However, with some exceptions in lean product development literature such as Morgan and Liker (2006), Kennedy et al. (2008) and Oosterwal (2010), A3 thinking is mainly applied for solving problems in the manufacturing shop floor. Alan Ward on the other hand realised that PDCA was not thoroughly efficient in product development and as a result introduced the Look Ask Model Discuss Act (LAMDA) learning cycle (Domb and Radeka, 2009). Recent research by Mohd-Saad et al. (2012) merges A3 template with the LAMDA learning cycle in order to increase problem solving capabilities more suitable for lean product development. This section revealed that the awareness of a knowledge environment is apparent and that it represents an important area of discussion in lean product development research, although there is not a common agreement or definition to clarify its existence. From this point of view knowledge management represents an important research area that requires more attention in lean product development and therefore will be reviewed in the following section.

3.4 Knowledge Management

Knowledge Management is based on the theory that organisations have to function in a knowledge based or centric way, which was established by Nonaka (1991; 1994), Kogut and Zander (1992), Grant (1996) and Lee (1993). The knowledge management community mainly discusses knowledge in explicit and tacit nature which was popularised by Nonaka (1991). Explicit knowledge refers to that kind of knowledge that can be articulated (Nickols, 2000) and represented in a formal way using universal symbols and characters (Choo, 2000; Nonaka and Krogh, 2009). On the other hand, tacit knowledge is regarded as difficult to express and articulate (Nonaka, 1991; Fulton and Pal, 2005) due to its subjective nature (Tiwana, 2002) as well as the fact that it is mainly embedded in individual work routines (Kogut and Zander, 1992). In addition to the recognition of tacit and explicit knowledge the knowledge management community also widely adopted Nonaka and Takeuchi's (1995) related theory of knowledge conversion, describing how to transfer tacit into explicit knowledge and vice versa in four different modes, namely socialisation, externalisation, combination and internalisation, as illustrated in Figure 3.8.

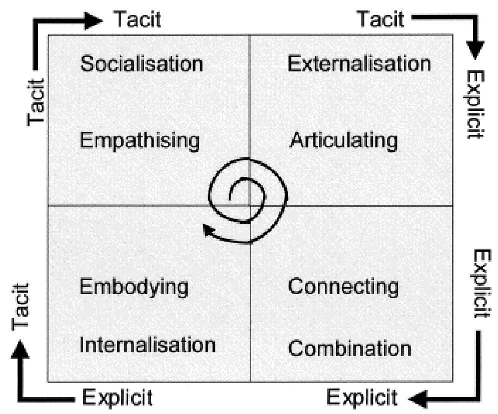


Figure 3.8 Modes of Knowledge Conversion from Nonakaet al. (2000)

Knowledge creation is mainly regarded as a continuous interaction between the four modes of knowledge conversion and manifests itself in an ever repeating spiral within a certain context and place (Nonaka and Konno, 1998; Nonaka et al., 2000). The aforementioned has proved very influential in knowledge management (Bolisani and Scarso, 1999; Abdullah et al., 2006; Choo and de Alvarenga Neto, 2010). However, adoption was also found in other disciplines such as manufacturing (Matsudaira, 2010) and information technology (Lopez-Nicolas and Soto-Acosta, 2010). Schulze and Hoegl

(2006) studied the effects of such knowledge conversion in new product development and suggest a deployment strategy for each of the four knowledge conversion modes as they have different influence at different product development phases. Critics of the knowledge conversion theory mainly argue about the conception and accuracy of tacit knowledge (Nickols, 2000; Hildreth and Kimble, 2002; Abdullah et al., 2006) which outlines the philosophical cornerstone of the developed principles in knowledge management as Nonaka and Konno (1998) stated that capturing tacit knowledge equals trying to 'express the inexpressible'. However, not necessarily all companies value knowledge as the most important asset, instead paying more attention to the resulting products and sales (Chen and Holsapple, 2009).

3.4.1 Knowledge Management in Product Development

It was also during research into product development that Takeuchi and Nonaka (1986) realised the importance of knowledge transfer and learning organisations. In product development most knowledge is regarded to be of tacit nature (Goffin and Koners, 2011, Goffin et al. 2010). New products developed are mainly based on previous projects or designs (Kalogerakis, 2010; McMahon et al., 2004) and are vital for long term success in manufacturing organisations (Cousins et al., 2011; Liker and Morgan, 2011; Gautam and Singh, 2008). Previous research reported that most of the product life cycle cost is committed in the early design stages (Shehab and Abdalla, 2006; 2001; Asiedu and Gu, 1998; Dowlatshahi, 1992). Hence, the capability to develop successful products depends highly on the quality of knowledge to support decision making in product development (Liker and Morgan, 2011).

Successful companies in the automotive industry, for example, globally share knowledge within different product platforms and modular toolkit systems (Wimmer, 2012). Also, the use of virtual reality during product design and development has become common practice in this industry. Examples include the implementation of simulation and testing in drive assistance systems (Nentwig et al., 2011) and the performance of entire product validation cycles (Bade et al., 2011) before making physical prototypes. Managing product development knowledge of such extent requires the exchange and integration of huge data sets from different product development functions in order to generate one complete system that supports the creation of new knowledge. As a result the complexity of knowledge increases to fulfil ever increasing market demand, especially for companies operating in an environment where knowledge has an increased life span, and hence face challenges in managing product development knowledge (Chen et al., 2010).

3.4.2 Knowledge Based Engineering

Knowledge based engineering aims to reduce the mundane and time consuming routine tasks in product development (Skarka, 2007; Stokes, 2001; Sandberg, 2003). It is a particular application of knowledge management, dealing with explicit rule based knowledge representation that can be embedded in computer aided design (Copper et al., 1999; Bermell-Garcia and Fan, 2008; Choo, 2000). This requires the use of advanced software technologies that support building domain specific knowledge models to solve engineering problems (Stokes, 2001; Studer, 1998). Hence, knowledge based engineering can be found in various applications in product design and development. Examples include multidisciplinary aircraft design (La Rocca and Van Toorren 2007; 2010), fixture design (Skarka, 2007; Hunter Alarcon et.al, 2010) and design for manufacturing (Rodriguez and Al-Ashaab, 2005; 2007).

The consideration of tacit knowledge, on the other hand, is not thoroughly addressed in knowledge based engineering, although it is a vital source in product development (Stein et al., 2003). Verhagen and Curran (2010) also argue that knowledge based engineering should focus more on the knowledge re-use side and that knowledge modelling frameworks, such as MOKA (Stokes, 2001) and CommonKADS (Schreiber et al., 2000) initially developed to support the implementation of knowledge based systems in a structured way are becoming increasingly outdated. Nevertheless, knowledge based engineering provides a considerable application which addresses certain key stages of the knowledge life cycle stages in product development, which among others will be presented in the next section.

3.5 Knowledge Life Cycle

A Knowledge Life Cycle (KLC) can be described as process with a conceptual framework that produces knowledge (Firestone and McElroy, 2003) using a sequence of stages within, which are designated different tasks and techniques. Its terminology was driven by Nonaka's (1991) work on the knowledge creating company, whereby when deployed in organisations is also referred to as knowledge management framework (Bukowitz and Willians, 1999) entailing how to manage adapted stages of the knowledge life cycle (McElroy, 2003). The review presented in this section is shown in

Table 3.1 and covers the KLC title, sequence of stages, evidence of closed loop case study in product development and whether or not the KLCs address LeanPD. Hence, this research is related to product development; additional knowledge life cycles adapted to support developing knowledge based engineering systems are reviewed and presented in Table 3.2.

The stages of the Bukowitz and Williams (1999) knowledge life cycle are divided into a tactical and strategic dimension, of which a core element represents knowledge-based assets, such as knowledge repositories and organisational intelligence. The first four stages of get, use, learn and contribute are tactical and driven by met and lost market opportunities or demands. The strategic dimension includes the stages of asses, build and sustain, and divest, which are triggered by changes in the macro environment. Alavi and Leidner (2001) outline that knowledge creation, knowledge storage and retrieval, knowledge transfer and knowledge application represent interdependent processes embodied in organizational knowledge management, which members can have different ways of participation as well as preferences for supportive tools. Also Bhatt (2000) outlines the interdependency of knowledge life cycle phases that largely depend on the knowledge adoption, meaning to ensure knowledge reusability by standardising the relevance interpretation of existing knowledge.

Table 3.1 Sequence of Knowledge Life Cycle Stages

Reference	Title	Sequence of Stages	Case Study in Product Development	Addressing Lean Product Development
Bukowitz and Williams (1999)	Knowledge Management Process Framework	Get, Use, Learn, Contribute, Assess, Build and Sustain, Divest	NO	NO
Bhatt (2000)	Knowledge Development Cycle	Knowledge Creation, Knowledge Adoption, Knowledge Distribution, Knowledge Review and Revision	NO	NO
Nissen et al. (2000)	Knowledge Management Life Cycle	Create, Organise, Formalize, Distribute, Apply, Evolve	NO	NO
Alavi and Leidner (2001)	Organizational Knowledge Management Processes	Knowledge Creation, Knowledge Storage/Retrieval, Knowledge Transfer, Knowledge Application	NO	NO
Birkinshaw and Sheehan (2002)	Knowledge Life Cycle	Creation, Mobilization, Diffusion, Commoditization	NO	NO
Schaefer et al. (2002)	Knowledge Life Cycle	Creation, Documentation, Transfer and Reuse	NO	NO

Reference	Title	Sequence of Stages	Case Study in Product Development	Addressing Lean Product Development
McElroy (2003); Firestone and McElroy (2003)	Knowledge Life Cycle	Individual and Group Learning, Knowledge Claim Formulation, Information Acquisition, Knowledge Validation, Knowledge Integration	NO	NO
Paukert et al. (2003)	Innovation Knowledge Life Cycle	Select Relevant Knowledge, Apply Knowledge, Gather Experience, Rate Experience, Share Experience	NO	NO
Salisbury (2003; 2008)	Ongoing Lifecycle of Knowledge in Organisations	Knowledge Creation, Preservation, Dissemination and Application	NO	NO
Jashapara (2004)	Knowledge Life Cycle	Discovering Knowledge, Generating Knowledge, Evaluating Knowledge, Sharing Knowledge, Leveraging Knowledge	NO	NO
Heisig (2006)	Framework for Integration of Knowledge Management	Create, Store, Share, Apply	NO	NO
Kennedy et al. (2008)	Closed Loop Lean Knowledge Management	Find or Create it, Document it, Organise it, Review it, Generalise for Reusability, Reorganise it for Reuse, provide when needed, Central to reviews, Maintain it, Improve it	In Theoretical Case Study	YES
Ben Miled et al. (2010)	Knowledge Life Cycle	Generating Knowledge, Storing Knowledge, Transferring Knowledge, Reusing Knowledge	NO	NO
Dalkir (2011)	Integrated Knowledge Management Cycle	Capture and Creation, Sharing and Dissemination, Acquisition and Application	NO	NO

Birkinshaw and Sheehan (2002) believe that knowledge is not static and that knowledge management tools are not universally applicable and therefore need to be chosen according to the different stages of the knowledge life cycle. Also Heisig (2006) underlines that central knowledge life cycle activities of create, store, share and apply build an interlinked process and require thorough investigation of supportive techniques. However these stages can also incorporate subsequent activities, for instance storing knowledge is described by Ben Miled et al. (2010) as identifying, structuring as well as integrating organisational knowledge.

McElroy's (2003) knowledge life cycle was developed with an increased focus on the demand side process addressing production and validation of knowledge claims (Chao et al., 2009), though the latter is regarded as difficult to validate in real cases (de Barros Campos, 2008). Jashapara (2004) believes that current perspectives of tacit and explicit knowledge are from narrow logical behaviour, hence emphasising on related soft aspects such as organisational learning in the stages of generating and leveraging knowledge. The knowledge life cycle of Paukert et al. (2003) on the other hand focuses on innovation, in which problem solving is seen as the key activity to gather experience as well as results in new knowledge for the share experience stage. Salisbury (2003; 2008) also outlines that disseminated and applied knowledge continuously supports knowledge creation resulting from solving problems.

Schaefer et al. (2002) on the other hand consider knowledge reuse as the benchmarking of the external environment in order to apply best practices developed in other organisations. Kennedy et al. (2008) introduced the terminology of closed loop lean knowledge management based on studying the Toyota product development system. Although its application is based on a theoretical case study and key stages are vaguely described, Kennedy et al. (2008) is the only work which explains a vision of closed loop of knowledge life cycle activities within the research area of lean product development.

For the knowledge life cycles, as presented in Table 3.1, it was observed that there is no common use of terminologies to describe stages as well as the knowledge life cycle framework itself. For example, the stages of information acquisition (McElroy, 2003), generating knowledge (Jashapara, 2004), get (Bukowitz and Williams, 1999) and capture (Dalkir, 2011) describe the same activity. In fact Heisig (2009) identified over 166 different terms to describe knowledge life cycle activities after reviewing 160 knowledge management frameworks, which were categorised into four mainly discussed groups, these being use, identify, create, acquire, share and store. Reason for this could include the fact that new knowledge life cycles evolve by integrating or synthesising key elements of previous work as well as by reconsidering or enhancing elements of initially proposed approaches. Therefore similar elements are likely to reoccur among the knowledge life cycles.

Dalkir (2011) for example, proposes an integrated knowledge management cycle based on studying previous work from Wiig (1993), Meyer and Zack (1996), Buckowitz and Williams (1999) and McElroy (2003). Consequently, similar elements reoccur, for instance endorsing a community of practice as an environment for knowledge sharing is apparent in the Dalkir (2011), Buckowitz and Williams (1999) as well as McElroy's (2003) knowledge life cycles. Nissen et al. (2000) on the other hand synthesises the previous research of Despres and Chauvel (1999) and Davenport and Prusak (1998) but also reconsiders phases within the initially proposed approach by Nissen (1999), such as substituting phases of knowledge capture with knowledge creation in order to additionally cover knowledge conversion as part of the knowledge life cycle.

The review of knowledge life cycle also outlines differences in the consideration of implementation, for instance McElroy (1999) focuses on the integration of new knowledge claims, whereby Bukowitz and Williams (1999) and Jashapara (2004) address key principles and soft aspects in organisational high level knowledge management. On the whole, much focus was directed to manifesting new ideas of knowledge management into a framework, though less focus was directed towards applying the knowledge life cycle in real life case studies, especially in product development, as shown in Table 3.1.

3.5.1 Knowledge Life Cycles to support developing Knowledge Based Engineering systems

Rodriguez and Al-Ashaab's (2007) knowledge life cycle was adapted to develop a knowledge web based system to enhance design for manufacturing as well as collaborative product development in the injection moulding domain (Rodriguez and Al-Ashaab, 2005). CommonKADS, MOKA and KNOMAD are modelling frameworks that support the development of knowledge based systems in a structured way. CommonKADS provides different perspectives to model the organisational environment as well as its functional behaviour (Studer, 1998; Kingston and Macintosh, 2000) mainly addressing knowledge life cycle stages of distribute and foster use, as shown in Table 3.2.

MOKA was inspired by the methods of KADS and adopted ideas of modularity in order to separate the formal model into controllable portions focusing mainly on the capture and formalisation of engineering knowledge (Stokes, 2001). The knowledge life cycle of MOKA was partially adopted by Torres et al. (2010) and Skarka (2007), by using the knowledge capture (ICARE) forms to capture domain specific knowledge. However, Torres et al. (2010) outlined that designers considered the use of such detailed templates and the activity of knowledge capturing as a burden.

Table 3.2 Sequence of Knowledge Life Cycle Stages to support developing Knowledge Based Engineering Systems

Reference	Title	Sequence of Stages	Case Study in Product Development	Addressing Lean Product Development
Rodriguez and Al-Ashaab (2005; 2007)	Knowledge Modelling Process	Identify, Capture and Standardise, Represent, Implement, Use	YES	NO
Common KADS (Schreiber et al., 2000)	Activities in Knowledge Management	Identify, Plan, Acquire, Distribute, Foster Use, Maintain, Dispose	Partially	NO
MOKA (Stokes, 2001)	Knowledge Based Engineering Life Cycle	Identify, Justify Capture, Formalize Package, Activate	Partially	NO
KNOMAD Curran et al. (2010)	Methodology for Knowledge Based Engineering	Knowledge Capture, Normalisation, Organisation, Modelling, Analysis, Delivery	YES	NO

Curran et al. (2010) argued that MOKA does not provide solutions for how the knowledge based engineering application is actually used in product design and that it does not consider multidisciplinary design optimization. Consequently, Curran et al. (2010) developed a methodology termed KNOMAD and presented a use-case validation that addresses its knowledge life cycle stages, as presented in Table 3.2

Identifying the right knowledge was considered in the knowledge life cycles of MOKA (Stokes, 2001), CommonKADS (Schreiber et al., 2000) and Rodriguez and Al-Ashaab (2007). Stenzel and Purroy (2007) state that knowledge is mainly available, personal or formalised in manuals and that ways of approaching experts require rigorous investigation. Hence, approaches to knowledge identification in product development differ, including content analysis (Salisbury; 2008), benchmarking (Schaefer et al., 2002), classification (Fu et al., 2006; Tama and Reidsema, 2010) or interviews and process diagrams (Cross and Sivaloganathan, 2007).

Matsumoto et al. (2005) address the necessity of proper knowledge identification before capturing, which is seen as an obstacle due to the fact that the definition of knowledge itself is very vague. Knowledge capturing is another key stage of the knowledge life cycle that most research in product development addresses by providing structured and customised knowledge capturing templates for domain specific problems (Bryson 2009; Poolton et al., 2010; Lee et al., 2006; Mahl and Krikler, 2007; Ferrer et al; 2010, Sharif and Kayis, 2007). Angelis and Fernandes (2007) argue that current practices for product and process improvement lack ergonomic processes and adequate tools for knowledge capturing. Matsumoto et al. (2005) on the other hand, suggest that knowledge capturing should not follow a rigid process and that there is no distinct or universal applicable way of knowledge capturing, after realising that a structured knowledge capture template within multiple groups of participants resulted in different contents being documented. Goffin and Koners (2011) suggest that the appropriate usage metaphors and stories have significant impact on tacit knowledge capture and generation in post-project review meetings.

Once knowledge is captured, knowledge representation becomes a vital stage of the knowledge life cycle to consider a computational use on the demand side as well as facilitate understanding knowledge through visual representation (Stokes, 2001). Two knowledge representation techniques are mainly applied in product development, namely object oriented and concept maps. In the former knowledge objects are structured in units of code and arranged hierarchically in classes, subclasses and instances, enabling a class to inherit the state and behaviour from its superclass. Objects contain variables or attributes, in which behaviour is interrelated and processed using rules (Meyer, 1997; Devedzic, 1999, 2001; Labrousse and Bernard, 2008). Object oriented knowledge representation is mainly found in domain specific knowledge based engineering applications (Stokes, 2001), whereby concept maps find increased use in knowledge communication and visualisation as well as enhancement of information search in web based applications (Carvalho et al., 2001; Canas et al., 2005). Concept maps are a graphical two-dimensional display of concepts, enclosed in circles or boxes of some type, which are connected by a line indicating brief relationships between pairs of concepts using verbs, phrases or forming propositions (Canas et al., 2005; Novak and Canas, 2008).

On the whole, the knowledge life cycles adapted to support the development of knowledge based systems as presented in Table 3.2, focus mainly on the explicit knowledge identification, capture and representation as well as validating through specific case based applications. However less attention was directed to tacit knowledge as well as the process of actual knowledge capture embedded during product development activities that have to be undertaken by design engineers less experienced in maintaining such systems.

3.6 Challenges in Product Development Knowledge Management

Although the previous sections outlined several capabilities, knowledge management is yet to be recognised throughout all aspects of product development. In order to investigate reported challenges in product development, publications were targeted that discussed related themes regarding either the demand for explanation or justification of encountered conditions, or which questioned subject related aspects of knowledge management.

Such challenge-related themes are discussed in different ways. Alavi and Leidner (2001) for example, identify research issues in the knowledge management process, whereas Heisig (2009) identifies critical success factors as named in knowledge management frameworks found in science, practice, associations and standardization bodies. It is difficult therefore, to find a single piece of research that addresses a wide range of challenges. In reality, these types of research did not focus on identifying challenges of managing product development knowledge in the first place. However, a discussion of challenge-related themes could be identified as a result of the adapted research methods. The literature review revealed the following three types of work based on the research method:

- Work based on secondary data resulting from reviewing and reflecting published sources
- Work based on empirical data resulting from industrial survey research
- Work based on empirical data resulting from direct observation in the company to perform a case study.

The work type based on secondary data discusses challenge-related themes in different subject areas. These are organisational knowledge management (Alavi and Leidner,2001; Ammar-Khodja and Bernard, 2008; Heisig 2009), learning in project teams in new product development (Edmondson and Nembhard, 2009), knowledge management in manufacturing (Baxter et al., 2009) and engineering design (McMahon et al., 2004), and knowledge-based engineering (Verhagen and Curran, 2010).

The second work type is based on empirical data resulting from industrial survey research. This includes research in the subject area of knowledge management systems (Alavi and Leidner, 1999), information management in engineering SMEs (Hicks et al., 2006; Hicks, 2007) and product innovation (Kalogerakis, 2010). Survey research discussing challenge-related themes in the particular subject area of new product development include supplier knowledge exchange (Cousins et al., 2011), knowledge management (Madhavan and Grover, 1998), inter-firm knowledge transfer (Knudesen, 2007), knowledge creation (Schulze and Hoegl, 2006) and lessons learnt (Goffin and Koners, 2011; Koners and Goffin, 2007).

The third type of work discussing challenge-related themes is based on direct observation within the industrial environment. These include subject areas of lean product development implementation (Morgan and Liker, 2011) as well as knowledge sharing (Bradfield and Gao, 2007) and collaboration Salisbury (2008) in new product development.

Given the above, twenty articles have been reviewed according to the discussed challenge-related themes and presented in Table 3.3. A total of fifty nine challenge-related themes have been identified and categorised into eight groups. The numbers in brackets, as illustrated in Table 3.3, correspond to the number of similar themes within the discussed group. For example, knowledge-access was raised as a demand for justification in two articles, namely by Kalogerakis et al. (2010) and Schulze and Hoegl (2006), hence the number 2 is shown in brackets. The following paragraphs presents the identified challenge-related themes based on similar group discussion as listed in Table 3.3.

Most of the reviewed articles discuss challenge-related themes with regard to knowledge processes such as -transfer, -storage, -mapping, -access, -identification and -creation. Kalogerakis et al. (2010) for example, identified the lack of a formal process for decision taking and stated that engineers have limited access to knowledge sources that support product innovation. Moreover, Schulze and Hoegl (2006) identify the combination of explicit knowledge as particularly challenging during knowledge transfer in product development. The demands of exploring supporting knowledge management techniques includes knowledge mapping (Baxter et al., 2009), knowledge representation (McMahon et al., 2004; Liker and Morgan, 2011) and knowledge identification (Salisbury, 2008; Baxter et al., 2009).

Another group of discussion themes refers to the management of information covering challenge-related themes of information; these being -flow, -excess, -redundancy, -transfer and -prioritisation. It is evident that information management is subject to a large quantity of legacy information (McMahon et al., 2004) embedding redundant (Madhavan and Grover, 1998) or flawed (Hicks, 2007) information into its challenge. In addition, the translation of information into new products (Cousins et al., 2011), as well as definition and prioritisation of information (Bradfield and Gao, 2007) is seen as challenging when exchanging knowledge in product development.

Table 3.3 Groups of Challenge-related Themes Discussed in Reviewed Articles

No	Groups of challenge-related themes discussed in reviewed articles	
1	Knowledge	(3) -transfer (Alavi and Leidner, 2001) -process (Kalogerakis et al., 2010) -combination (Schulze and Hoegl, 2006) (3) -storage and retrieval (Alavi and Leidner, 2001; Baxter et al., 2009) -discovery (Liker and Morgan, 2011) (3) -mapping (Baxter et al., 2009) -representation (McMahon et al., 2004; Liker and Morgan, 2011) (2) -access (Kalogerakis et al., 2010; Schulze and Hoegl, 2006) (2) -identification (Salisbury, 2008, Baxter et al., 2009) (1) -creation (Alavi and Leidner, 2001)
2	Information	(4) -flow (Hicks, 2007) -processing (Alavi and Leidner, 1999; Cousinset al., 2011) -distribution (Bradfield and Gao, 2007) (2) -excess (Hicks, 2007) -quantity (McMahon et al., 2004) (2) -redundancy (Madhavan and Grover, 1998) -flaw (Hicks, 2007) (1) -transfer (Cousinset al., 2011) (1) -translation into new products (Cousinset al., 2011) (1) -definition and prioritisation (Bradfield and Gao, 2007)
3	Communication	(6) -cross-functional (Ammar-Khodja and Bernard, 2008; Edmondson and Nembhard, 2009; Knudsen, 2007; Liker and Morgan, 2011) -interaction (Madhavan and Grover, 1998; Goffin and Koners, 2011) (2) -temporary team membership (Edmondson and Nembhard, 2009) -team distance (Schulze and Hoegl, 2006)
4	Application	(3) -process (Alavi and Leidner, 2001) -strategy (Baxter et al., 2009; Schulze and Hoegl, 2006) (3) -variety -re-use -integrity (Verhagen and Curran, 2010) (1) -automation (Baxter et al., 2009)
5	Management	(3) -practices (Alavi and Leidner, 1999; Heisig, 2009; Goffin and Koners, 2011) (2) -misconceptions (Ammar-Khodja and Bernard, 2008, Alavi and Leidner, 1999) (1) -quantification of advantages (Verhagen and Curran, 2010) (1) -outsourcing of technical knowledge (Liker and Morgan, 2011)
6	Organisation	(2) -complexity of projects (Edmondson and Nembhard, 2009) -structures (Heisig, 2009) (2) -integration (Baxter et al., 2009) -embeddedness (Edmondson and Nembhard, 2009) (1) -environment (Knudsen, 2007)
7	Human	(4) -factors (Knudsen, 2007; Heisig, 2009) -boundaries (Edmondson and Nembhard, 2009) -trust (Madhavan and Grover, 1998)
8	Technology	(3) -capabilities (Heisig, 2009, Alavi and Leidner, 2001) -strategy (Ammar-Khodja and Bernard, 2008)

With regards to communication, challenge-related themes include cross-functional as well as team related barriers. The latter include temporary team membership (Edmondson and Nembhard, 2009) as well as team distance (Schulze and Hoegl, 2006). The application side of knowledge triggers various possibilities, though a challenge remains to address its integrity and re-use side (Verhagen and Curran, 2010) in particular as an automatic mechanism that support the acquisition of new knowledge (Baxter et al., 2009).

Challenge-related themes discussed regarding the aspect of management demand enhancement of current practices, such as involvement of key management in mentoring or storytelling roles during post project reviews, as identified by Goffin and Koners (2011). Other management challenge-related themes include misconceptions with regard to extent of knowledge capturing (Ammar-Khodja and Bernard, 2008) or definition of knowledge management systems (Alavi and Leidner, 1999), quantification of advantages (Verhagen and Curran, 2010) as well as the outsourcing of technical knowledge (Liker and Morgan, 2011).

Discussed challenge-related themes with regard to the corporate organisation highlight the magnitude of project complexity (Edmondson and Nembhard, 2009) and organisational structures (Heisig, 2009) that consequently trigger challenges of integration (Baxter et al., 2009) or embeddedness (Edmondson and Nembhard, 2009). Knudsen (2007) also highlights the organisational environment, in particular the difficulty of expressing customer need in inter-firm relationships.

Human related challenge-themes include discussion about associated factors, such as effect of routine tasks on product innovation (Knudsen 2007), fluid team boundaries (Edmondson and Nembhard, 2009) as well as trust in technical competence among product development team members (Madhavan and Grover, 1998). Challenge-related themes with regard to technology include demand for extended IT capabilities (Alavi and Leidner, 2001) as well as alignment of technology and knowledge management with corporate strategy (Ammar-Khodja and Bernard, 2008).

The above presented the identified challenge-related themes in managing product development knowledge and their inter-relationship based on similar areas of discussion. This is summarised in Table 3.3, which also provides the platform to relate such themes to the industrial challenges, as presented later in section 4.4.

3.7 Research Gap Analysis and Summary

Research in lean product development and its principles is evolving and therefore it presents a wide range of research areas that have not been thoroughly addressed yet. In total three research gaps have been identified as a result of the literature review and presented as follows.

***Research Gap 1**:* There is a lack of understanding of the current *industrial challenges in managing product development knowledge* that is essential to create a knowledge environment for lean product development implementation.

The literature review in Section 3.6 has revealed a need for further empirical research to enhance current understanding of challenges encountered in managing product development knowledge. These include primarily a focus on identifying an extended range of industrial challenges as well as the collection of first hand empirical data purely from key industrial informants. Although the knowledge environment is a key area of discussion, the transition from traditional to lean product development occurred without a thorough investigation of current challenges in managing product development knowledge.

Research Gap 2: There is no clear *framework and sequence of stages* that will assist the creation of a knowledge environment to support lean product development.

The literature review clearly defines that lean product development is a knowledge intensive process; however key stages of the knowledge life cycle have not been thoroughly addressed. In fact, the literature review in this chapter provided for the first time four categories, as well as corresponding tools and techniques, associated with a knowledge environment. Consequently a specific knowledge life cycle is yet to be developed to facilitate the implementation of such knowledge environment, which in return requires the consideration of adequate knowledge capture and re-use stages suitable during lean product development.

***Research Gap 3**:* There is a lack of evidence and method how to *dynamically capture and provide* knowledge as a result of problem solving in a lean product development knowledge environment.

Previous research has focused on designing knowledge capturing templates for particular knowledge domains. However there is no method to facilitate the dynamic knowledge capturing whilst it is being created during product development. During problem development knowledge creation is mainly related to solving engineering problems, as it is widely agreed that product development is an ever repeating problem solving activity. Although the lean product development community refers to problem solving as knowledge creation, the lifecycle of knowledge in particular capturing and provision has not been thoroughly addressed yet. In this context there is lack of evidence in the form of a case study that will entail a closed loop of knowledge life cycle stages in lean product development.

Chapter 4

INDUSTRIAL FIELD STUDY AND CHALLENGES

4.1 Introduction

The previous chapter presented an extensive review of the related literature. This chapter focuses on providing practical evidence on industrial perspectives and challenges in managing product development knowledge. The scope of this chapter is illustrated in Figure 4.1 and contains three main research studies undertaken, namely industrial requirements, industrial field study and industrial challenges of which the adapted research methodology was presented in section 2.2.

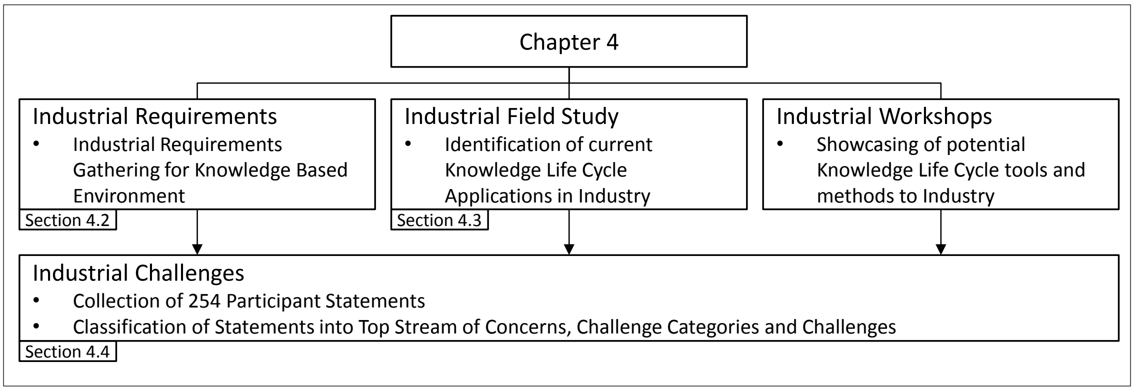


Figure 4.1 Scope of Chapter 4

Industrial requirements gathering for a knowledge based environment, Section 4.2, was conducted within the industrial partners of the LeanPPD consortium. The industrial field study, Section 4.3, was then expanded to a total of eleven companies in order to identify current knowledge life cycle applications in industry. Four of the eleven companies operated each in the automotive and aerospace sector and one each in the medical equipment, home appliances and metal forming sector. As shown in Figure 4.1, the classification of industrial challenges was undertaken using statements collected during industrial requirements gathering and industrial field study as well as industrial workshops and therefore it represents the core research contribution of this chapter. Industrial workshops included the showcasing of potential knowledge life cycle methods and tools to a selected number of four companies as part of the research methodology presented in Section 2.2. The profile of companies and participants contributing to this chapter is presented in Table 4.1. Due to confidentiality, companies have been named in alphabetical order.

Table 4.1 Profile of Companies and Participants

Total Number of Companies (A…K)			**11**
	In Sectors	Automotive (A, B, C, J)	4
		Aerospace (E, F, G, I)	4
		Medical Equipment (H)	1
		Home Appliances (D)	1
		Metal Forming (K)	1
	Ratio of Company Participation	Industrial Requirements	5 / 11
		Industrial Field Study	11 / 11
		Industrial Workshops	4 / 11
Total Number of Participants			**42**
	Job Roles	Product Designers	11
		Product Development Engineers	31
	Work Experience in Product Design and Development	0 – 5 Years	2
		5 – 10 Years	8
		10 – 20 Years	21
		Over 20 Years	11
	Ratio of Participation	Industrial Requirements	5 / 42
		Industrial Field Study	33 / 42
		Industrial Workshops	12 / 42

In the context of this research, the job roles of the 42 participants were categorised into product designers and product development engineers, thus representing the key informants, these being the main people who will use the knowledge to support decision taking to influence the shaping of the product under development. The importance of such decision taking is vital, as it is reported that 70% of the manufacturing cost is committed during the early design stage (Asiedu and Gu, 1998; Dowlatshahi, 1992). Product designers are those who generate the engineering solutions to meet customer needs in the form of geometry and functions. They are also responsible for modifying the design based on the feedback from other product development functions, such as manufacturing, product assurance or marketing. Product development engineers within the context of the research reported in this research are responsible for defining the engineering details, such as material, stress, quality assurance, testing and simulation as well as product manufacturability and manufacturing process planning and improvement. Nowadays however, in addition to traditional perspectives, some of the product designers and engineers take on management responsibilities to a certain extent, such as project management, as part of their job characteristics. This research benefited from such rich working experiences of the participants. As shown in Table 4.1, half of the participants had work experience in product development of between ten and twenty years, and eleven participants had over twenty years of work experience.

4.2 Industrial Requirements

The gathering of requirements was undertaken as part of the LeanPPD project within the five industrial collaborators, as presented in Section 1.5. Rios et al. (2006) outlines two different types of requirements, namely functional and non-functional. Functional requirements outline scope, boundaries as well as conforming rules of a system whereby non-functional requirements describe the look and feel such as usability and visualisation. The standard requirements gathering template as put forward during the LeanPPD project is shown in Figure 4.2. Given the above, the Cranfield team then jointly defined functional and non-functional requirements for the knowledge based architecture and the knowledge based environment. For the purpose of this research thesis only the functional requirements of the knowledge based environment will be presented as the main contributor to the research.

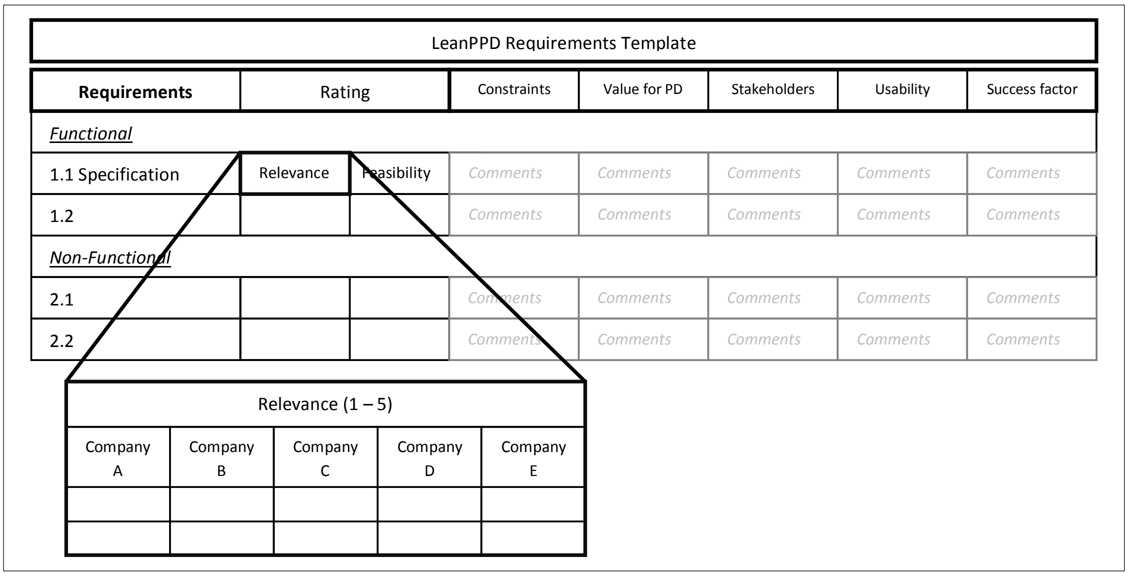


Figure 4.2 Industrial Requirements Template (Al-Ashaab et al., 2010)

The standard template included ratings for relevance and feasibility to implement between 1 and 5 for the listed specifications and also comment cells for constraints, value to product development, stakeholders, usability and success factors. The functional requirements were defined in November 2009 at the early stage of the research. Nevertheless, it aimed to describe main elements of a knowledge environment identified in lean product development literature, presented in Section 3.3, from a functional view according to the understanding at that time. For example, problem solving was not seen as a key principle back then and therefore does not appear in any of the requirements or specification.

Table 4.2 Functional Requirements for LeanPPD Knowledge Based Environment (Al-Ashaab et al., 2010)

No.	Functional Requirement and Specifications	Average Rating Relevance	Average Rating Feasibility
FR1	**The KB Environment shall bring together relevant previous projects in order for the designers to initiate a new set of designs**	**82%**	**62%**
	1.1 The KB Environment shall capture and structure previous projects in order to have a standardised project knowledge repository to support new projects		
	1.2 The KB Environment shall facilitate inter-relation of previous projects		
FR2	**The KB Environment shall enable a search function in order to locate and retrieve the most relevant project information**	**88%**	**59%**
	2.1 The KB Environment shall provide a mechanism based on knowledge discovery techniques to identify trends of solutions from previous projects		
	2.2 The KB Environment shall facilitate key word searches		
	2.3 The KB Environment shall enable the user to retrieve all the relevant information for a specific component or subsystem		
FR3	**The KB Environment shall provide a function to visualise knowledge required to support engineering decision taking**	**90%**	**60%**
	3.1 The KB Environment shall provide a means of viewing the most important knowledge relevant to a problem encountered during the product development in a concise and easy-to-digest format		
	3.2 The KB Environment shall provide a function to produce trade-off curves, which illustrate the relationship between key characteristics and parameters of different design solutions from previous and current projects		
FR4	**Dynamic Capture of knowledge created by engineers throughout the product development process**	**94%**	**52%**
	4.1 The KB Environment shall provide a workspace to input different types of design knowledge to be captured, shared and utilised in real time among the development team		
	4.2 The KB Environment shall provide a structured template in order to capture and present in a standardised format the knowledge gained through the progression of the project		
FR5	**The KB Environment shall provide a function to recall the key lessons learnt at the various stages of the product development process.**	**92%**	**80%**
	5.1 The Function shall provide lessons learnt, at both the systems and subsystems levels		

The functional requirements and their sub levelled specifications defined are illustrated in Table 4.2. The ratings in Table 4.2 represent the average percentage of overall specifications rated for a functional requirement. For example if a company rated a specification with “4” the percentage would equal 80% representing one fifth for the overall value as five companies participated.

The relevance of the functional requirements has been rated very high, between 82% and 94%. This means that the companies in general agree with the presented functional requirements and its specifications. However the feasibility of implementation was rated comparably much lower, at between 52% and 62%. Although companies agree its relevance, it is less feasible to implement such advanced ideas as endorsed in the lean product development research.

The functional requirement FR4 dynamic knowledge capturing, which to date is not addressed in lean product development literature, represents the highest value in relevance at 94% as well as the lowest value in feasibility to implement, with 54%. Reasons for the low rated feasibility to implement can be extracted as challenges of managing product development knowledge in Section 4.4, hence the comments captured in the requirements template were used by the author in order to categorise industrial challenges. The completed requirements gathering templates including all comments are included in Appendix A. The next section presents the results of the industrial field study.

4.3 Industrial Field Study

The industrial field study was performed to identify current industrial practices related to knowledge life cycle application. Appendix B contains section number 3 of the LeanPPD questionnaire, entitled knowledge based engineering and environment, as designed by the researcher to support the study. This section does not present the entire extent of questions raised, but a selection of the most meaningful ones depicted to have particular influence in this research. The numbering of the following questions corresponds to the numbering as presented in the LeanPPD questionnaire in Appendix B.

Question 3.1 (see page 233): *From your personal experience, how important do you assess the following sources of Knowledge?*

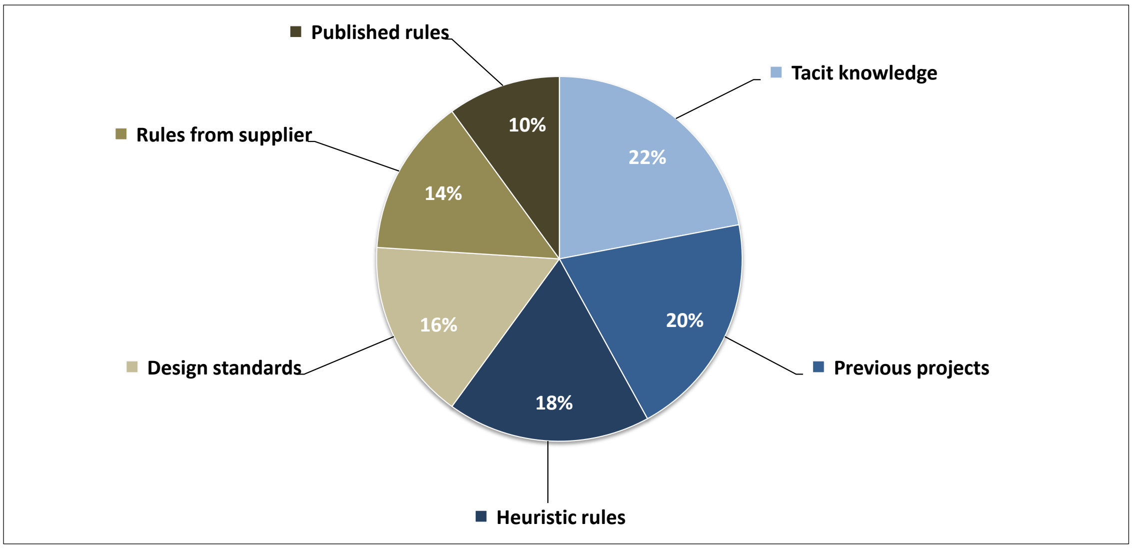


Figure 4.3 Distribution of Knowledge Sources – Combined Importance resulting from Question 3.1

Product development engineers ranked the importance of commonly used sources of knowledge. The result, as shown in Figure 4.3, outlines that the participants rated tacit knowledge as most important in product development. Another finding shows that in-house generated knowledge including tacit knowledge, previous projects and heuristic rules were considered to be more important sources (60%) as opposed to published or externally acquired rules and design standards (40%).

Question 3.4 (see page 235): *What methods are used in your company to realize that captured knowledge is re-used and shared during the product development process?*

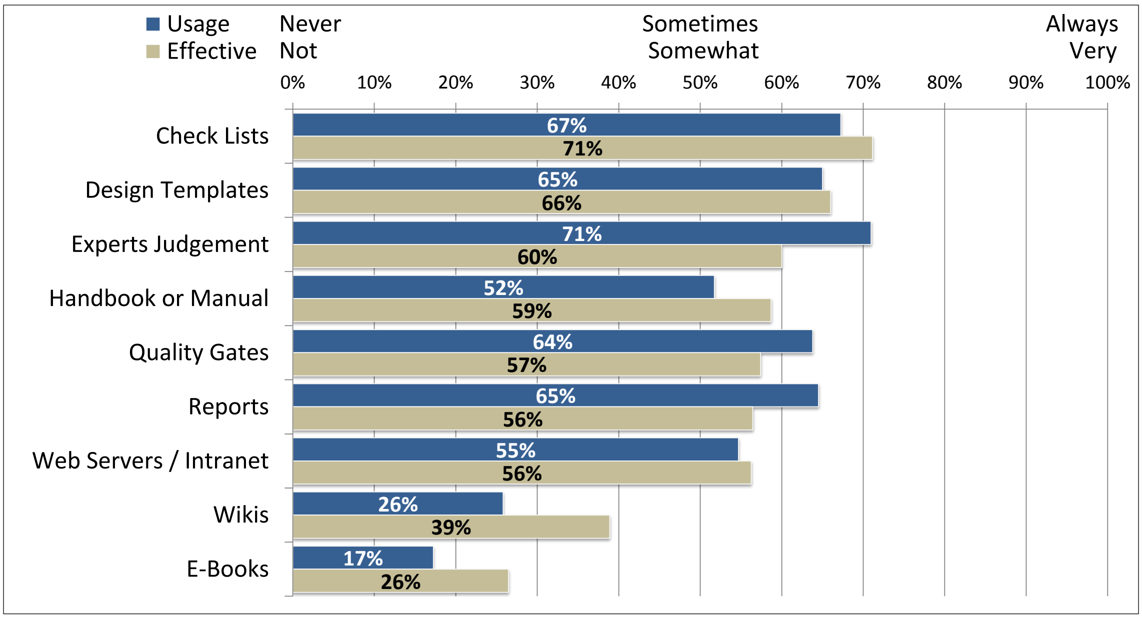


Figure 4.4 Knowledge Re-use and Sharing Methods in Industry resulting from Question 3.4

Although a number of methods are used to re-use and share knowledge in industry, the effectiveness and usage among them varies, as shown in Figure 4.4. This could be due to the fact that some of the methods have not been developed with a primary focus on the demand side of product designers and engineers. Nevertheless, checklists and design templates were rated highest by those who used them. Another finding is that using information technology such as internet and wikis or electronic forms for knowledge sharing was rated less effective than knowledge sharing through human interaction, such as expert judgement and quality gate reviews.

Question 3.6 (see page 235): *Please estimate in percentage how much of your work is related to routine and innovative Tasks?*

Question 3.7 (see page 236): *Please estimate how much, in percentage, do you rely on knowledge from previous project when designing a new product?*

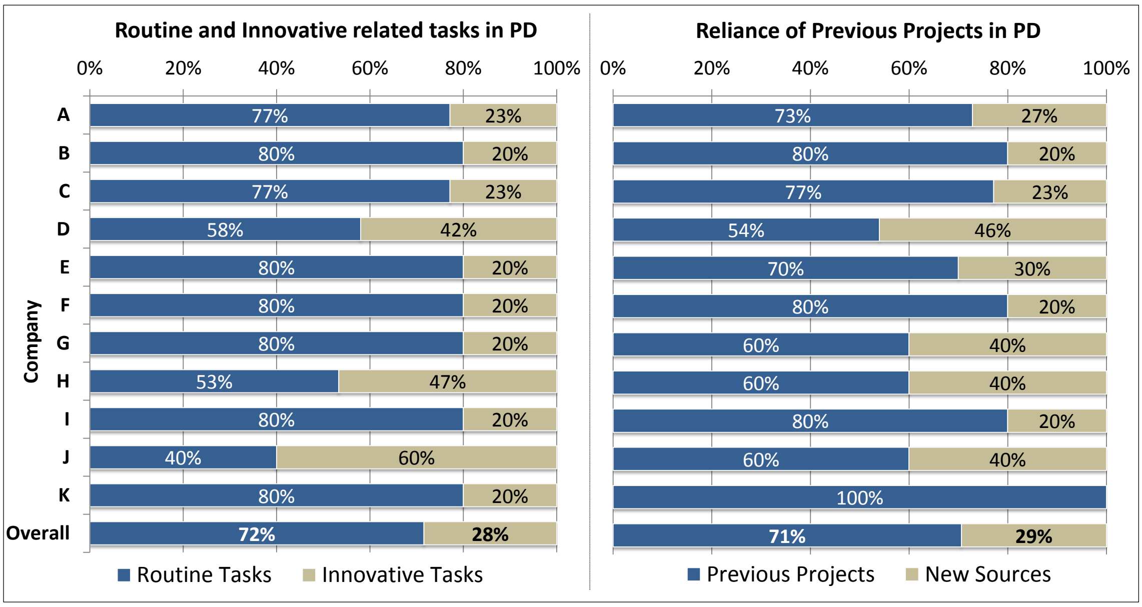


Figure 4.5 Tasks Distribution and Reliance on Previous Projects in Product Development resulting from Questions 3.6 and 3.7

One of the main advantages of knowledge based engineering was reported to be the reduction of the mundane and time consuming routine tasks in product development. Skarka (2007) and Stokes (2001) are both using the distribution of 80%-20% as a value to represent the ratio between the routine and innovative related tasks within product development processes. However, no evidence for these values is given and therefore the field study aims to provide a value for this distribution. An accurate value was difficult to achieve, as product development activities are not tangible or measurable.

Therefore, engineers were asked to estimate the percentage of time spent in routine and innovative related tasks. The overall results show that 72% of the time was estimated to be spent with routine and 28% with innovative related tasks. Although most of the interviewees stated that they spend 80% of their time on routine tasks, with the exception of three companies: D, H and J. Hence those three companies (D, H and J) operate in different sectors suggests that such distribution is dictated by the particular participant's job roles.

As product development is mainly based on previous design solutions, the engineers were asked to estimate the percentage they rely on knowledge from previous projects when designing a new product. The results indicate that engineers rely on average 71% on knowledge from previous projects when designing new products, as shown in Figure 4.5. Participants in company D from the home appliance sector expressed the least reliance of previous projects, whereby company K from the metal forming sector outlined a reliance of 100%. Companies that rely less on previous projects are either subject to progressive changes of product ranges and technologies or simply do not take the full advantage of this asset. Nevertheless the overall high reliance of 71% highlights the importance of previous projects as well as its created knowledge in product development.

Question 3.12 (see page 238): *How and which of the following data is stored at your company for a specific product during the entire product life cycle?*

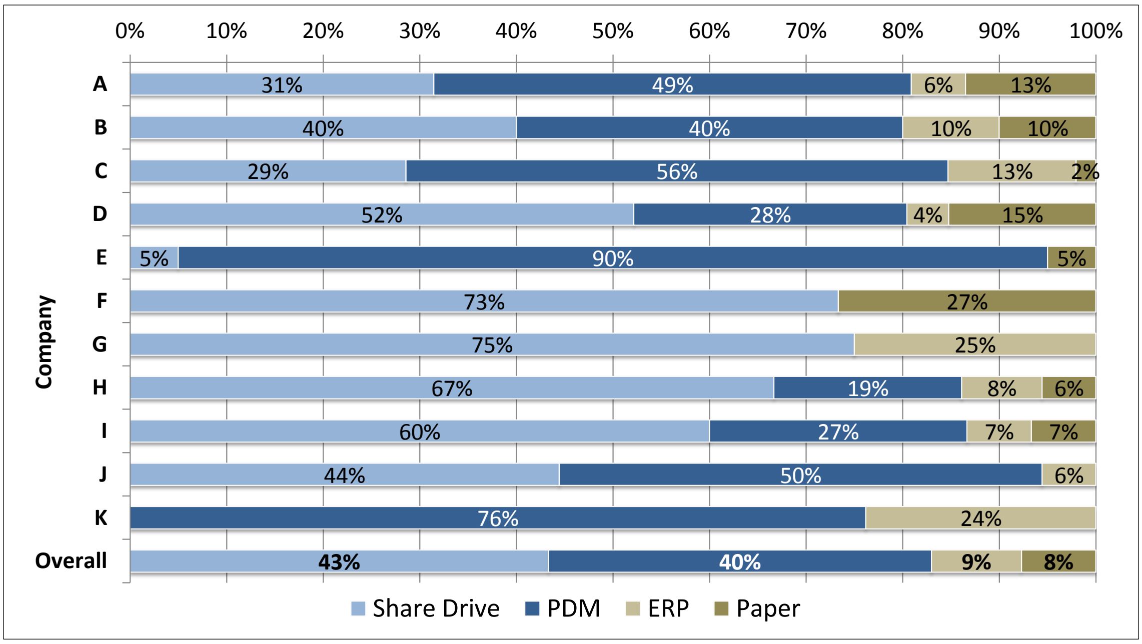


Figure 4.6 Knowledge Storage in Product Development resulting from Question 3.12

The industrial field study also aimed to investigate how companies compare with the idea of a centralised knowledge as presented in Section 3.3.2. Consequently, participants were asked to indicate where product development information, such as test reports, CAD files and bill of materials, is stored in the organisation. The results show that companies use multiple storage mediums, see Figure 4.6. However no effective centralised database was found. In fact 43% of product development information was stored in shared drives, only 30% in product data management (PDM) systems and 10% in enterprise resource planning systems (ERP) and paper form.

The results in Figure 4.6 outline differences among sectors. The companies participating from the automotive sector (A, B, C and J) stated that they stored from 40% to 56% of product development information on the PDM system. In the participating aerospace companies (E, F, G and I) the distribution varies. Whilst company E stated that 90% of product development information is stored in a PDM system, companies F, G, and I reveal that over 60% is stored on shared drives.

Question 3.13 (see page 239): *Do you think that problems in previous designs could have been prevented by the correct knowledge being provided at the right time?*

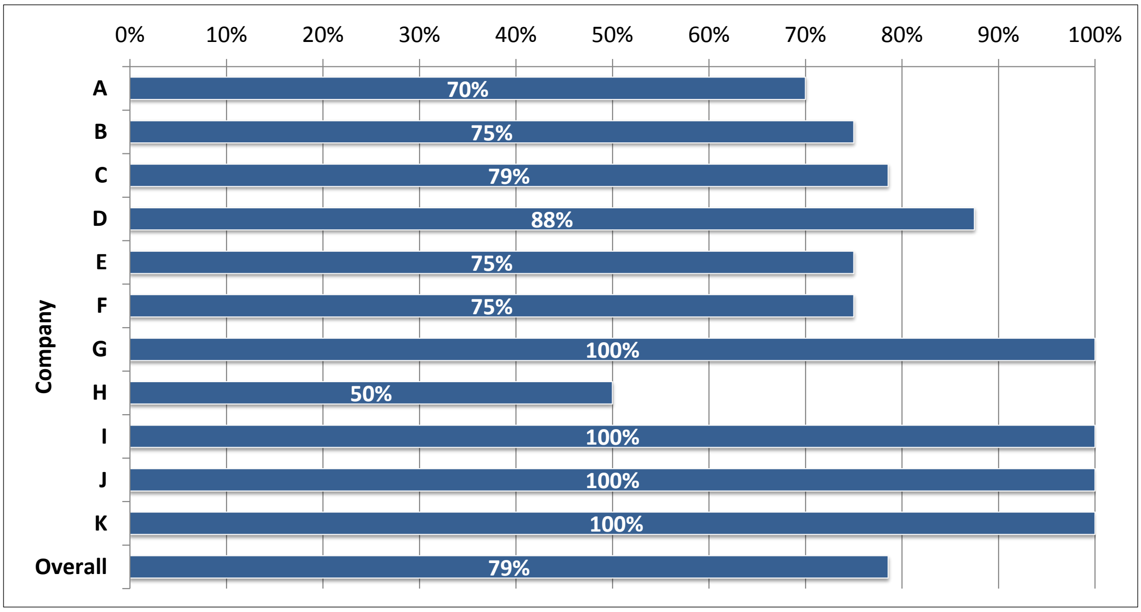


Figure 4.7 Percentage of Design Problems could be solved through accurate Knowledge Provision resulting from Question 3.13

During the industrial field study it was observed that product development teams focus primarily on current design problems, as opposed to learning and increasing enterprise knowledge. Information tends not to be pulled, however participants suggested that 79% of all design problems could have been prevented by the correct knowledge being provided in the right place at the right time, as shown in Figure 4.7. The lowest score for this indicator is 50% and was obtained from company H, which operates in the medical sector, hence outlining that sufficient knowledge does not exist on half of the design problems. Although companies G, I, J and K indicated that 100% of design problems could be solved via adequate knowledge provisions, such responses could still have implications among the different business functions within a company.

Question 3.14 (see page 239): *What challenges do you face with regards to managing product development knowledge?*

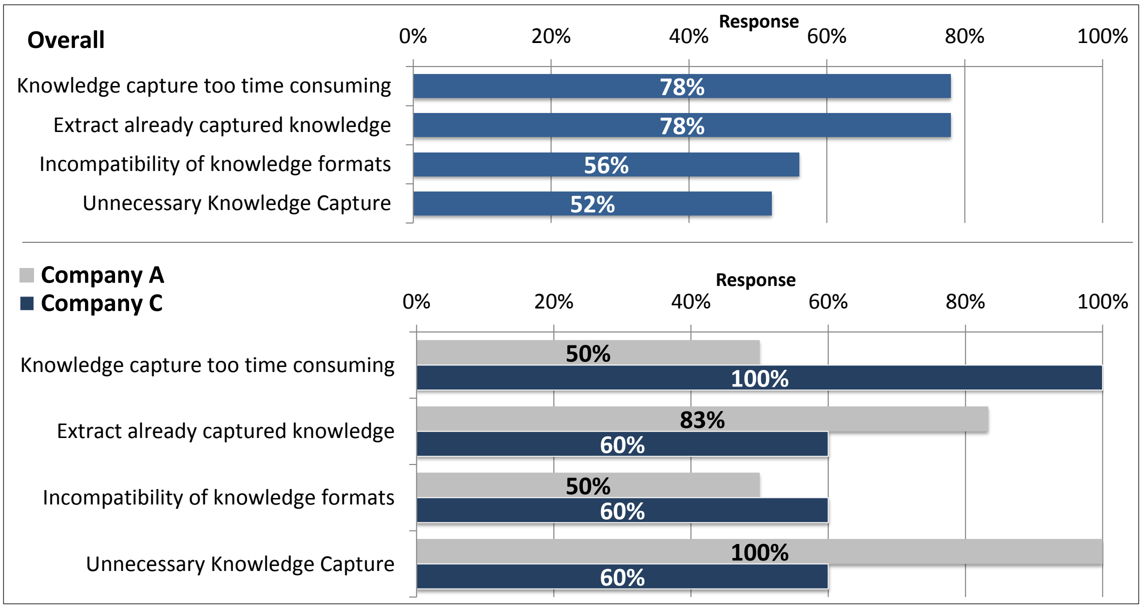


Figure 4.8 Initial Knowledge Management Challenges resulting from Question 3.14

In order to encourage a discussion of current issues during the industrial field study, four common challenges as shown in Figure 4.8 were presented to the participants in order to provide confirming evidence.

Knowledge capturing was considered time consuming by 78% of participants. The same amount, 78% of participants find it difficult to locate and extract knowledge which already has been captured and is available. Although both challenges received same rating, the distribution of responses varies between companies as well as participants, as shown in Figure 4.8. Whilst 100% of participants in company C stated knowledge capture as too time consuming significantly less, 50% expressed the same concern in company A. On the other hand extracting already captured knowledge was stated as much bigger concern for company A than for company C.

52% of participants suggested that documented knowledge tends to be overcrowded due to unnecessary knowledge capture and 56% that they also face knowledge format incompatibility problems.

The listed challenges in Figure 4.8 entail a huge significance in the related research. However, during the interaction with product development engineers it was evident that there is a much larger amount of challenges related to the managing product development knowledge that will be presented in following section.

4.4 Industrial Challenges in Managing Product Development Knowledge

This section describes the identification of challenges in managing product development knowledge from the perspective of the key informants by collecting statements from a total of 42 product development designers and engineers, as outlined in Table 4.1. The authors believe that it is vital to understand challenges of this nature in order to effectively manage knowledge in product development as well as to address the limitations of previous research as presented in Section 3.6.

The conduct of industrial requirements gathering, industrial field study and industrial workshops as illustrated in Figure 4.1 resulted in completed questionnaires, hand-written notes and voice records from which raw data was structured according to the responses of the 42 participants in alphabetical order (Participant1 = A, Participant2 = B, … Participant42 = AP). The data classification is based on thematic coding, suggested by Robson (2011) as a common approach for qualitative data analysis, adapting three levels of classification as shown in Table 4.3. The initial activity however of thematic coding comprised the generation of codes of 'states' in which the participant expresses general conditions experienced in the organisations (Robson, 2011) related to challenges in managing product development knowledge. This resulted in the generation of 254 relevant statements based on the participants' responses (A1...An, B1…Bn, … AP1…APn).

1st Level of Classification – Top Stream of Concerns

The first level classified themes by analysing repetitions of topics among the statements, which resulted in three top streams of concerns. 57% of the concerns raised were related to knowledge life cycle activities, as shown in Table 4.4. The second stream of concerns raised pointed towards difficulties in the operating product development environment and represented 35% of the overall captured statements. The third stream of concerns was related to management issues, which represented 8% of overall captured statements.

2nd Level of Classification - Challenge Categories

The second level of classification entailed the construction of thematic networks, meaning to classify sub-level challenge categories among the top stream of concerns. In total, eight challenge categories were identified, of which four resulted from top stream concerns of knowledge life cycle activities:

- Knowledge capture
- Knowledge sharing
- Knowledge use
- Knowledge provision

Three challenge categories resulted from the top stream of concerns in product development environment, these being:

- Complexity
- Integration
- Human factors

The top stream of concerns in management resulted in one challenge category, which was:

- Quantification of success

3rd Level of Classification -Challenges

Finally, in the third level of classification via thematic coding, the authors noted further patterns and themes as impacting on the challenge categories which resulted in the classification of particular challenges faced by the participants. In total, thirty eight challenges have been identified, as shown in Table 4.4. It should be noted that the percentages for this third level classification of challenges represent the contribution to a challenge category, not to the overall collected statements. This aims to focus on challenge categories rather than on isolated individual challenges. For example, the knowledge capture category consists of five challenges, namely content, structure, tacit knowledge, process and motivation as illustrated in Table 4.4. The challenge of structure contributes 19% to the challenge category of knowledge capture.

Table 4.3 shows three examples of how statement codes generated during the qualitative research were classified into corresponding categories. Statement codes V3 and AN1, for example, contain different wordings, although both correspond to the same key concern of ‘knowledge life cycle activities in product development’, challenge category of ‘knowledge capture’, as well as the same challenge of knowledge capturing ‘content’.

Table 4.3 Three Levels of Data Classification based on Thematic Coding

Statement Codes Examples	1st Level of Classification – Top Stream of Concerns (Themes)	2nd Level of Classification - Challenge Category (Thematic Networks)	3rd Level of Classification - Challenge (Interpretation)
V3:“…It has to be clear *what knowledge* needs to be *captured*…”	Knowledge Life Cycle Activities in Product Development	Knowledge Capture	Content
AN1:“…there is a big concern with *capturing quality of data*…”	Knowledge Life Cycle Activities in Product Development	Knowledge Capture	Content
D12:“…*success* should be measure by the *number* of lessons *retrieved* for a specific problem or context…”	Management	Quantification of Success	Regularity

Data quality tests are based on frequency count by providing the percentage of statements raised as corresponding to the top stream of concerns as well as the challenge categories, as illustrated in Table 4.4. In addition, challenges referred to in the following sections are checked against the reviewed literature in Section 3.6 for confirming evidence. This form of data quality test corresponds to triangulation by replicating findings from different sources (Robson, 2011). The following subsections contain detailed information of the identified 38 challenges in this research.

Table 4.4 Challenges in Managing Product Development Knowledge from Designers' and Engineers' Perspectives

Overall Collected statements

100% A total of 254 Statements Collected

1st Level of Classification - Top Stream of Concerns

57% related to: **1** Knowledge Life Cycle Activities in Product Development	**35%** related to: **2** Product Development Environment	**8%** related to: **3** Management

2nd Level of Classification - Challenge Categories

20% related to: 1.1 Knowledge Capture	**17%** related to: 1.2 Knowledge Sharing	**11%** related to: 1.3 Knowledge Use	**9%** related to: 1.4 Knowledge Provision	**15%** related to: 2.1 Complexity	**10%** related to: 2.2 Integration	**10%** related to: 2.3 Human Factors	**8%** related to: 3.1 Success Quantification

3rd Level of Classification - Challenges

Contribution to Challenge Category in %

1.1.1 41% Content	1.2.1 40% Communication	1.3.1 50% Ease	1.4.1 48% Form	2.1.1 36% Competitive Environment	2.2.1 50% IT Infrastructure	2.3.1 38% Awareness	3.1.1 30% Regularity
1.1.2 19% Structure	1.2.2 29% Retrieval	1.3.2 18% Consistency	1.4.2 30% Innovation	2.1.2 18% Company Structures	2.2.2 26% Decision Taking Activities	2.3.2 25% Responsibility	3.1.2 25% Time Reduction
1.1.3 14% Tacit Knowledge	1.2.3 11% Ownership	1.3.3 18% Administration	1.4.3 13% Time	2.1.3 15% Processes	2.2.3 12% Standardisation	2.3.3 16% Commitment	3.1.3 20% Quality Improvement
1.1.4 14% Process	1.2.4 11% Confidentiality	1.3.4 14% Methodology	1.4.4 9% Place	2.1.4 15% Relations	2.2.4 12% Format	2.3.4 12% Rush	3.1.4 15% Intellectual Capital Increase
1.1.5 12% Motivation	1.2.5 9% Storage			2.1.5 10% Customer Requirement		2.5.5 9% Sophistication	3.1.5 10% Cost Reduction
				2.1.6 6% People			

4.4.1 Challenges Related to Top Stream of Knowledge Life Cycle Activities

The main stream of top concerns related to knowledge life cycle activities representing 57% of all collected statements during the qualitative research. It resulted in the challenges categories of knowledge capture, knowledge sharing, knowledge use and knowledge provision, which will be described in the following sections.

4.4.1.1 Knowledge Capture Challenges

The challenge category of knowledge capturing is the highest rated, corresponding to 20% of overall collected statements. It consists of five challenges, which have the following contribution: content 41%, structure 19%, tacit knowledge 14%, process 14% and motivation 12%, as shown in Table 4.5.

Table 4.5 Knowledge Capture Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
1.1 Knowledge Capture	20%		
		1.1.1 Content	41%
		1.1.2 Structure	19%
		1.1.3 Tacit Knowledge	14%
		1.1.4 Process	14%
		1.1.5 Motivation	12%

During the qualitative research, the authors noticed that several companies have formal knowledge management initiatives whilst others do not. In both cases, the main challenge is to define what meaningful and useful knowledge should be captured and how. This relates to the **content** of the captured knowledge, which was the challenge mostly raised during this study. One observation about knowledge capture is that the content is not always at a sufficient level of detail. The detail is sometimes obsolete and in a format that is not easy to read and use. In addition, there exists the repetition of captured knowledge stored in different places, such as shared drives, personal notebooks and reports. These shortcomings make the task of capturing the inter-relations between the knowledge content even more difficult, as was expressed by a product development engineer in an automotive company, who wondered, *“How can we ensure that bad or misleading information is not captured and/or retained?”* The reviewed research outlined similar concerns, such as discovering useful information (Liker and Morgan, 2011) and knowledge identification (Salisbury, 2008; Baxter et al., 2009) which highlights a need for thorough knowledge identification. Moreover, Ammar-Khodja and Bernard (2008) outlined that it is not only impractical but also impossible, to capture and store the entire corporate knowledge. Hence, research and application of knowledge identification techniques require more attention in order to tackle this challenge, especially in product development.

Product development knowledge could be **structured** in many ways; for example, according to processes, projects, sub-systems, components or functions. Companies investigated in this research expressed a need for guidance on how to structure knowledge. This need was clearly expressed by a product development engineer of an automotive company, who stated that, *"Direction should be provided on how to structure the knowledge-based environment to facilitate efficient input and extraction of knowledge. Sometimes the defined structure can be a barrier to data entry. If the structure is too rigid and asks for information that does not seem relevant for that knowledge item, the user can be intimidated and not enter the information."* Previous research efforts in developing structured knowledge capturing templates, such as MOKA (Stokes, 2001) and CommonKADS (Schreiber et al., 2000) are decreasing in use (Verhagen and Curran, 2010). Also, the usage of rigid structured knowledge capturing templates could still result in capturing inadequate knowledge due to different perceptions among designers and engineers (Matsumoto et al., 2005).

There is general agreement among product development engineers that **tacit knowledge** is the most important source of knowledge in an enterprise. A major challenge for both academics and industry has always been to convert such knowledge into an explicit format. A product development engineer from a medical equipment company stated that *"Knowledge is all over the place, everywhere, but mainly in the heads of the engineers."* The phrase of "express the inexpressible" (Nonaka and Konno, 1998) might be a good way to convey this challenge.

The **process** of capturing knowledge is another challenge attributed to the current practice of performing documentation at the end of a project, when the involved personnel either forget key elements of the gained knowledge or they are already engaged in a new project.

Motivating the engineers to participate effectively in the process of knowledge capture is an important challenge, because many engineers perceive knowledge capturing to be a time-consuming task. Several companies reported that templates for knowledge capturing have been rejected by engineers who do not see the value of completing them. Therefore, an innovative method is required to seamlessly integrate the knowledge capturing process throughout the product development activities. A senior product designer from a metal manufacturing company expressed this concern, *"It is a challenge to discipline the engineers to follow the procedures, engineers look to do it the easy way."* In spite of the fact that this challenge forms only 12% of knowledge-capture challenges, the authors believe that tackling such a challenge will have considerable implication on the success of knowledge management initiatives in product development.

4.4.1.2 Knowledge Sharing Challenges

Knowledge sharing is the second highest rated challenge category, representing 17% of overall captured statements. It comprises five challenges, which have the following contribution: communication 40%, retrieval 29%, ownership 11%, confidentiality 11% and storage 9%, as shown in Table 4.6.

Table 4.6 Knowledge Sharing Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
1.2 Knowledge Sharing	17%		
		1.2.1 Communication	40%
		1.2.2 Retrieval	29%
		1.2.3 Ownership	11%
		1.2.4 Confidentiality	11%
		1.2.5 Storage	9%

Throughout the research**,** the participating engineers highlighted the issue of **Communications** among personnel involved in the product development as particularly important, which is reflected in the fact that it is the highest rated challenge in the category with a 40% contribution. Nevertheless, early-stage involvement of other functions in product development was welcomed everywhere in order to share the knowledge and experiences of the different disciplines. However, complex departmental structures and the focus on departmental functions, in combination with time pressure to complete the job were stated as the main reasons for a problem mainly expressed as over-the-wall communication. A product designer from an aerospace company stated, *"We have so many other things to do, so we didn't involve manufacturing on time."* A considerable amount of research, such as Edmondson and Nembhard (2009), Cousins et al. (2011), Madhavan and Grover (1998), Liker and Morgan (2011), Goffin and Koners (2011) and Knudesen (2007), has previously outlined the issues of communication or interaction between engineers. This research on the other hand, suggests that tackling the over-the-wall communication among multi-disciplinary engineers, as well as creating a culture of sharing without intimidation, needs prioritised attention in product development. The authors believe that product development knowledge could be communicated through simple methods, such as A3Report, trade-off curves and checklist, depending on the engineering application and type of knowledge. Although researchers in the area of lean product development welcome such methods (Liker and Morgan, 2011; Lindlof et al., 2012; Sobek et al., 1999), little effort has been directed to considering the entire life-cycle of knowledge, which is currently being addressed by the authors (Maksimovic et al., 2011). Another concern raised in the communication challenge was that human interaction could deteriorate due to the current implementation of the PLM tools by encouraging the task accomplishment through “clicks,” without considering how it could affect other employees. Moreover, it was observed that some companies purposely block communication between departments, in order to stimulate innovation with less distraction.

Knowledge **Retrieval**, which is the ability to extract knowledge from previous projects, is another challenge that should be addressed. One reason for such a challenge is that databases are overloaded with data duplications, unnecessary data and useless knowledge. Another reason is that most companies tend to capture data first then consider the retrieval mechanism later, which leads to a complex data structure. The industrial field study supports this fact, where 78% of participants stated that it is difficult to locate and extract knowledge which has already been captured and is available. A product development engineer in the automotive sector raised this concern, *“After five minutes of search the engineer gets bored and gives up and maybe never uses the retrieval function ever again.”* This challenge is largely apparent and as such is discussed in previous research, although in different terms including knowledge storage and retrieval (Alavai and Leidner, 2001; Baxter et al., 2009), knowledge discovery (Liker and Morgan, 2011), information excess (Hicks, 2007) and quantity of legacy information (McMahon et al., 2004).

Specific knowledge is bounded to a specific person; therefore, **ownership** is another challenge that needs to be considered in order to identify the ‘right person’, who has the skill and the authority to release and share the knowledge. An interesting finding during this study was that many engineers believe that key knowledge should not be owned by one person. This was confirmed by the following statement from an automotive product development engineer: *“It is not good to constrain the company* *to only one guy that knows everything.”* Despite the relatively small number of statements collected for this challenge, which totals an 11% contribution to the knowledge sharing challenge category, it was observed that ownership can have significant implications in certain organisational functions, especially in small departments, where the knowledge of individuals is vital for engineering decision taking.

Companies perceive it as a big risk that intellectual capital could be shared with competitors. The challenge is how to balance a healthy and beneficial sharing culture with the protection of its **confidential** competitive know-how. During this study, this challenge did not exhibit a considerable response: only an 11% contribution to challenge category. Nevertheless, it is expected that this category will have a higher level of impact in other industries, such as defence and pharmaceuticals, which were not considered in this study.

Storing knowledge is another challenge, as it was observed that useful knowledge is sometimes stored in a local PC drive or in shared folders without organised structures. Engineers want to have access to different documents from departments across the entire organisation, a task that they find difficult to achieve. Such a problem is highlighted in the literature by Schulze and Hoegl (2010) and Kalogerakis (2010) as limited access to knowledge sources that support new product development as well as product innovation. Also the industrial field study revealed that 52% of participants expressed that documented and stored knowledge tends to be overcrowded.

4.4.1.3 Knowledge Use Challenges

The challenge category of knowledge use represents 11% of the overall captured statements. It comprises four challenges, which have the following contributions: ease 50%, consistency 18%, administration 18% and methodology 14%, as shown in Table 4.7.

Table 4.7 Knowledge Use Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
1.3 Knowledge Use	11%		
		1.3.1 Ease	50%
		1.3.2 Consistency	18%
		1.3.3 Administration	18%
		1.3.4 Methodology	14%

Whilst capturing knowledge is important, the main challenge is how to use it. The challenge of ease represents the biggest contribution to the knowledge use category. Designers and engineers want **easy-to-use,** knowledge-based software tools that can be integrated smoothly within the existing CAD systems and other software packages used in different functions, such as manufacturing, cost, logistics, etc. *"A scalable level of the system usability as the platform should be used by different people coming from different contexts, background, with different expertise and skill of advanced computer-based interfaces,"* was stated by a product development engineer from a home appliances company.

There is an emphasis on the need for **consistency** in order to use knowledge beyond a single application. For example, the documentation of lessons learnt and the sharing of them do not usually end up in working practices. A senior product designer in the aerospace sector confirmed this challenge by raising the concern that *"Mistakes are repeated, fundamental physics are not understood."*

Having a knowledge-based software application is important. However, the real challenge is to maintain and **administrate** the software as the knowledge must be updated, and the software and hardware need to be upgraded. This also raises the challenge of software legacy. Engineers highlighted the importance of having a person with the skill to be responsible for this task. It is important to make the point that this is not an IT administration issue, but rather one of knowledge maintenance, which means that the responsible person should have the knowledge relating to product development. *"System administrators should have an extensive acquaintance about product development, technical specifications, computer aided systems and database management,"* as stated by a product development engineer in an automotive company.

Although the knowledge-based engineering applications are important to solve domain related problems, the engineers highlighted the importance of the **methodology** that should be used in order to get to the right solution. Such a methodology will help to provide the knowledge–based working environment that supports product development. However, this also requires supporting tools (Bradfield and Gao, 2007), implementation strategy (Baxter et al., 2010) and alignment of technology (Ammar-Khodja and Bernard, 2008) as individually mentioned in previous research.

4.4.1.4 Knowledge Provision Challenges

The challenge category of knowledge provision represents, with 9% of overall captured statements, the lowest rated challenge category in the top stream of concerns related to knowledge life cycle activities. It comprises four challenges, which have the following contributions: form 48%, innovation 30%, time 13% and place 9%, as shown in Table 4.8.

Table 4.8 Knowledge Provision Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
1.4 Knowledge Provision	9%		
		1.4.1 Form	48%
		1.4.2 Innovation	30%
		1.4.3 Time	13%
		1.4.4 Place	9%

The **form** of knowledge provision is a challenge, as most of the engineers are not aware or sure of the different applications of software-based knowledge provision, such as knowledge-based engineering, trade-off curves or checklists. They are good however, at expressing the requirements of the possible knowledge-based solutions.

The amount and type of knowledge that has to be provided to engineers in order to support **innovation** in product design and development is another issue that needs to be addressed. A product development engineer in an automotive company highlighted: *"If the exposures about previous projects seem too dominant, innovations could be hemmed."* This challenge also addresses the issue of **timely** provision of the accurate knowledge at the right **place**. In the industrial field study, 56% of the participating engineers indicated that they face knowledge format incompatibility problems. *"Knowledge has to be provided at the right time, place, people and format. Otherwise you develop a product that does not meet the customer requirements,"* as stated by a design engineer in an aerospace company.

4.4.2 Challenges Related to Top Stream of Product Development Environment

Key concerns raised with regard to the top stream of product development environment represented 35% in this study. It resulted in three challenges categories, namely complexity, integration and human factors, which will be described in the following sections.

4.4.2.1 Complexity Challenges

The challenge category of complexity is the highest rated in the top stream of product development environment, corresponding to 15% of overall collected statements. As shown in Table 4.9, it comprises six challenges which have the following contributions: competitive environment 36%, company structures 18%, processes 15%, relations 15%, customer requirement 10% and people 6%.

Table 4.9 Complexity Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
2.1 Complexity	15%		
		2.1.1 Competitive Environment	36%
		2.1.2 Company Structures	18%
		2.1.3 Processes	15%
		2.1.4 Relations	15%
		2.1.5 Customer Requirement	10%
		2.1.6 People	6%

The **competitive environment** challenge contributed 36% within the complexity category. It was observed that knowledge capturing is not regarded as a priority activity in industry because of the internal working environment as well as the external market conditions. A typical pressure on designers and engineers is the demand for shorter product development times, which might result in delivering a product that has not necessarily reached a mature level. This competitive environment puts the priority of managing the knowledge in a secondary position. The following testimonies were captured during the qualitative research: *"Knowledge sharing is hemmed due to time pressure to deliver fully validated products,"* from a product development engineer in a home appliances company. *"New design projects are put into competition internally...department has to fight internally for the project,"* from a product development engineer in an automotive company. This challenge highlights the need for developing methods that can seamlessly be integrated into the product development activities and can assist the transformation of knowledge management activities into the daily routine of designers and engineers.

Company Structures make it difficult to empower engineers to initiate and implement knowledge capturing and sharing among the different departments and projects. In addition, sharing knowledge on a global basis is growing in complexity due to different time zones, cultures, skills, infrastructure and regulations (Ichijo and Nonaka, 2007; Ichijo and Kohlbacher, 2007). A product development engineer in an automotive company stated, *"Complex department structure will complicate the knowledge capturing."*

Complex product development **processes** in organisations make it difficult to implement suitable knowledge management practices for capturing, creating, re-using and sharing knowledge. This is due to two factors; firstly, many processes make it hard to envision the inter-relations between the different disciplines, as similarly outlined by Ammar-Khodja and Bernard (2008) as cross-disciplinary boundaries. The second factor is the natural complexity of knowledge flow between the different departments and projects, as similarly highlighted by Hicks (2007), Hicks et al. (2006) and Cousins et al. (2011).

Relations refer to the challenges of managing knowledge related to the product structure as well as the relations between the different activities in product development. In some companies the current inter-relations between the different components and sub-assemblies of a product are not well understood; as a consequence, these inter-relations are not well captured within the product model structure implemented on a PLM/PDM platform. Hence, knowledge of these inter-relations is key to having a successful product development project. This challenge is due to the increase in complexity of the product structure due to increased customer demands, which as a product design in an aerospace company highlighted, *"Just a little change in design (feature), cascades to the immense PLM files structure."* The challenge of relations has a big influence in representing technical knowledge visually to facilitate problem solving activities (Liker and Morgan, 2011). In order to provide more understanding of such relations, McMahon et al. (2004) suggest embedding the rationale behind the captured knowledge content.

Customer Requirements knowledge challenge is related to the fact that requirements regularly evolve and change throughout product development. These changes in requirements usually have a major impact on the smooth development of technology associated with the products, and also with the process of capturing the newly created knowledge. The following testimony was captured during the research: *"The customer does sometimes not know what he wants, requirements become negotiable and evolve during product development,"* from a product development engineer in an automotive company. Also, Knudsen (2007) confirms such testimony as a barrier in inter-firm knowledge transfer during new product development.

The **number of people** involved in designing and developing a product, including suppliers and customers, can be very high, which makes it challenging to control the number of people involved in knowledge acquisition and sharing. Another aspect of this challenge is the fluctuation inside departments or temporary team membership, as discussed by Edmondson and Nembhard (2009).

4.4.2.2 Integration Challenges

The challenge category of integration represents 10% of overall captured statements. It comprises four challenges, which have the following contributions: IT infrastructure 50%, decision taking activities 26%, standardisation 12% and format 12%, as shown in Table 4.10.

Table 4.10 Integration Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
2.2 Integration	10%		
		2.2.1 IT Infrastructure	50%
		2.2.2 Decision Taking Activities	26%
		2.2.3 Standardisation	12%
		2.2.4 Format	12%

Integration with the **IT infrastructure** is the top rated challenge with a contribution of 50% of statements. The main challenge that arises is the diversity of commercial solutions to support different activities of product design, engineering and development. Manufacturing companies demand that any knowledge-based solutions should have a smooth or direct integration to their current IT infrastructure, mainly the CAD system.

A higher interest is shown in maximising the use of the existing technologies rather than developing new ones. It is a fact that complete product data integration throughout its lifecycle on a PLM/PDM platform is still a big challenge; hence, adding the knowledge to this task makes it an even bigger challenge. A product development engineer in an automotive company for example, requested that: *"The CAD system is the base of the development process - other applications must cooperate with this."* The demand for having a knowledge-based solution that is directly integrated into a company's current IT infrastructure, mainly the CAD system, is appreciated. However, it should be emphasised that not all types of knowledge could be integrated in this manner, as pointed out by Ammar-Khodja and Bernard (2008). Previous research, such as that of Baxter et al. (2009), Alavi and Leidner (2001) and Hicks et al. (2006), outlines the issues of integrating knowledge in the existing IT infrastructures. Cousins et al. (2011) suggests a closer relationship between technology monitoring and the integration with product lines and corporate functions. Nevertheless, this area requires further investigation, as it remains a major concern for manufacturing organisations.

Knowledge-proven **Decision Taking** is vital throughout the product development process. However, in most cases decision taking is based on multiple variables, such as cost, package, weight and performance. The inter-relation between the key decisions taken is difficult to capture and understand, as designers usually have to trade-off between multiple variables. Therefore, managing and providing the required knowledge to support the engineering decision making is a big challenge.

Standardisation is a challenge that needs to be met in order to maintain an effective product development process. Understanding and implementing process and design standards is not well-practised throughout the product development process. The challenge occurs when attempting to standardise a large range of documents, e.g. CAD files, test reports, etc., not only from different sources and functions, but also from different perspectives and mind-sets. The challenge of standardisation also covers the standard **format** of the data exchange among the different CAD/CAE/CAM systems. The following testimony was captured from a product development engineer in the automotive sector: *"Knowledge standardisation all around the enterprise is necessary. To standardise files, drawings and other documents from hundreds of different formats to serve different software tools is a real challenge. Who provides the knowledge?"* This challenge is also supported by the industrial field study, where engineers stated that 43% of product development media was stored on shared drives rather than in a centralised database.

4.4.2.3 Human Factors Challenges

The challenge category of human factors represents 10% of overall captured statements. It comprises five challenges with the following contributions: awareness 38%, responsibility 25%, commitment 16%, rush 12% and sophistication 9%, as shown in Table 4.11.

Table 4.11 Human Factors Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
2.3 Human Factors	10%		
		2.3.1 Awareness	38%
		2.3.2 Responsibility	25%
		2.3.3 Commitment	16%
		2.3.4 Rush	12%
		2.3.5 Sophistication	9%

When asking product development engineers about their experience in managing product development knowledge, the responses were mainly that they were **not aware** of the principles of knowledge management. However, the authors found evidence that companies use, for example, rules, formulas and constraints integrated within their CAD systems, without realising that they actually have a version of a knowledge-based engineering system.

Elements of managing knowledge in product development are found in many companies; however, transforming product development into a knowledge-based environment cannot be realised by relevant engineers without making them aware of such techniques and offering them formal training of knowledge management principles. This was also highlighted by a product designer in the aerospace industry: *"Knowledge management is under-represented in the design world."* Similarly, Baxter et al. (2009) express a need that industry should be more involved in primary knowledge management research, especially enhancing early stages of concept selection. The authors believe that in general, the challenge category of human factors requires special attention in product development. The challenge of awareness, in particular, highlights that a practical approach to knowledge management, as undertaken in this study through industrial workshops, is essential in order to raise interest and then the commitment of designers and engineers.

The product development engineers hold the main **responsibility** for the final physical product. Therefore, this can result in a high risk of losing self-confidence or reputation if a product fails. This leads to the issue of trusting the provided knowledge to support decision making, which Madhavan and Grover (1998) discuss as trust in technical competence as well as faith in others' intentions.

The **Commitment** of designers and engineers to participate effectively in capturing, re-using and sharing knowledge with other colleagues and projects is a big challenge in product development. The same case applies to capturing quality data of the finished project for re-use in new projects. This challenge is due to several issues, as follows:

- Human factors in the sense that people can become reluctant to perform the mundane tasks of knowledge documentation
- Their belief that such a task is an extra load on them. This supports the finding of the industrial field study, where 78% of the engineers interviewed mentioned that knowledge capturing is considered to be time consuming
- Some engineers are unwilling to share their knowledge in order not to lose their value within the company.

A product designer in the aerospace industry described a concern regarding commitment: *"At some point, engineers just end up ticking the boxes in the check lists."* The challenge of commitment potentially causes fluid team boundaries in the long term, in which case Edmondson and Nembhard (2009) endorse leadership skill as well as conflict management training.

The challenge of **rush** has two different facets: firstly, engineers expect too fast results when using supportive tools. Secondly, in terms of problem solving, engineers tend to focus on solving current problems rather than establishing and sustaining a knowledge base.

It is a common perception that any improvement of current practices has to be accomplished by using **sophisticated** high-end software tools. On the contrary, the authors support the finding from the industry that the implementation of knowledge in software is not always the best solution. Also, previous research suggests simple management approaches, such as enhancement of informal meetings (Schulze and Hoegl, 2006) as well as embodying mentoring and storytelling roles during post project reviews (Goffin and Koners, 2011).

4.4.3 Challenges Related to Top Stream of Management

The top stream concerns in management, covering 8% of the overall collected statements, resulted in one challenges category, the quantification of success. This challenge category, with its 8% contribution, is the lowest score of statements collected. This implies that the quantification of success is not one of the major concerns for product designers and engineers.

4.4.3.1 Quantification of Success Challenges

For the people responsible for managing the product development knowledge it is always a challenge to quantitatively justify benefits to their managers and the end users of the knowledge. The challenge category of quantification of success consists of five challenges that have the following contributions: regularity 30%, time reduction 25%, quality improvement 20%, intellectual capital increase 15%, and cost reduction 10%, as shown in Table 4.12.

Table 4.12 Quantification of Success Challenges

Challenge Category	Overall Statements Percentage	Challenges	Contribution to Challenge Category
3.1 Success Quantification	8%		
		3.1.1 Regularity	30%
		3.1.2 Time Reduction	25%
		3.1.3 Quality Improvement	20%
		3.1.4 Intellectual Capital Increase	15%
		3.1.5 Cost Reduction	10%

The challenge of **regularity** is based on the quantitative measurement of how often the product development engineers make use of the provided knowledge-based software, as well as how often they participate in the activities of, for example, updating a knowledge base. A product designer in an aerospace company stated**:** *"If product development engineers use the developed software then it is a success."* Although the authors perceive the challenge of regularity as highly significant, it is usually hard to convince top management to invest in knowledge management initiatives in order to conduct such projects.

Knowledge-based decision making is likely to result in significant **time reduction** in the product development process, where such time reductions will depend on the type of activity within the process. The main challenge is of how to determine the total impact of knowledge-based decision making on the entire product development time reduction. In addition, measuring the success in terms of time reduction can be very difficult in product development. This is because specific product development activities, e.g. assigning of tolerances, do not usually have rigid timeframes, as opposed to, for example, manufacturing processes. It is a challenge to define the success factors within time reduction, considering the fact that it is necessary to first spend time on knowledge capturing before taking the benefit. *"Measuring time for* *data retrieval and product design development could be a success factor,"* according to a product development engineer in home appliances.

The challenge of **quality improvement** and i**ncrease of intellectual capital** are of similar natures. The primary challenge, in both cases, lies in the short term justification of developing better products as a result of knowledge proven decision making. Research in knowledge-based engineering, such as Stokes (2001) and Skarka (2007), uses the arguments of eliminating routine design tasks to enhance the focus on innovation. Another example is capturing the knowledge created as a result of solving design problems in order to reduce design iterations. Kalogerakis (2010) and Goffin and Koners (2011) agree that product development is a problem-solving activity, though companies forget to capture and reuse the created knowledge of this kind in order to improve product quality. The bottom line to realise any form of knowledge management initiatives is the funding, which directly relates to the challenge of success quantification in terms of **cost reduction.**

4.5 Chapter Summary

This chapter presented an industry based research for industrial requirements gathering, industrial field study and identification of challenges in managing product development knowledge. The requirements gathering outlined a huge relevance for the provided functional requirements based on the understanding from lean product development literature though still there are a much lower feasibilities to implement of such principles in reality.

During the interaction with industry in the field study it was observed that knowledge management has not manifested itself as a common practice in product design and development. One key factor is definitely the lack of adoptable and efficient set of techniques and its associated asks to such a highly complex and in some cases intangible process of product development. The enhancement of engineering capabilities and more specifically knowledge life cycle activities requires more attention. Main sources of product development knowledge are elaborated from previous projects and therefore it is important to capture such knowledge whilst developing a product in order to make reusable knowledge for the future.

This chapter also presented an industry based research related to challenges in managing product development knowledge from the perspective of designers and engineers. In contrast to previous research, presented in Section 3.6, that highlighted isolated aspects of some of the captured challenges, this study presented a structured and comprehensive approach to capture, classify and evaluate a wide range of apparent challenges in product development.

Chapter 5

DEVELOPMENT OF A NOVEL LEAN KNOWLEDGE LIFE CYCLE FRAMEWORK

5.1 Introduction

Chapter 5 covers the Lean Knowledge Life Cycle (LeanKLC) development to support the transformation into a lean product development knowledge environment, thus presenting the core contribution of the aspired research aim as defined back in Section 1.3.

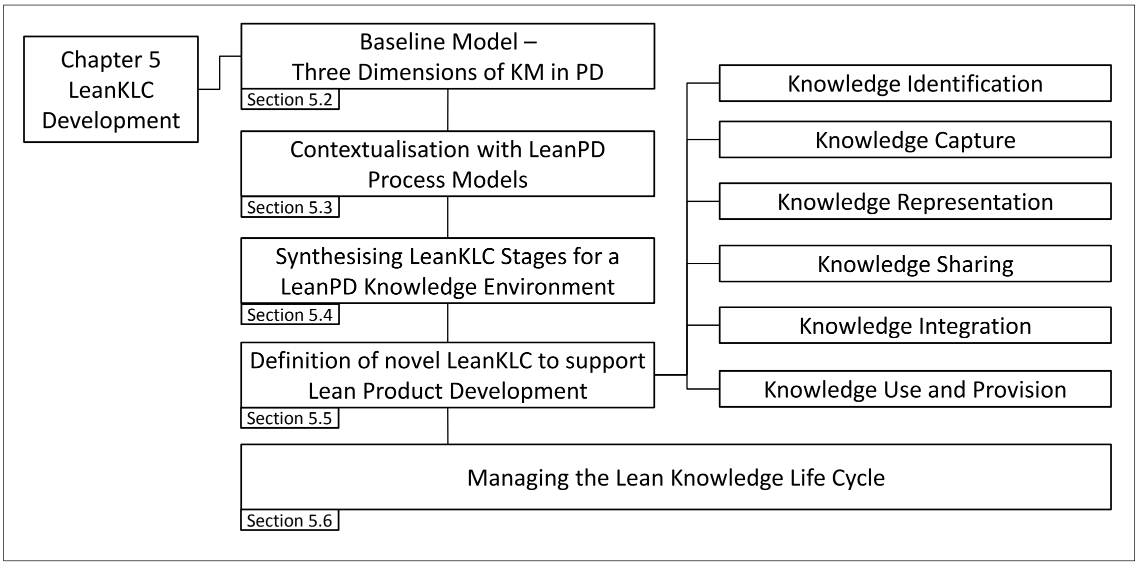


Figure 5.1 Scope of Chapter 5

The development of the LeanKLC framework starts with a baseline model in order to understand the dimensions of knowledge management in product development in Section 5.2, followed by the of the baseline model being contextualised with existing lean product development process models in Section 5.3. Synthesising of LeanKLC stages for a lean product development knowledge environment is presented in Section

5.4 as illustrated in Figure 5.1. Then, Section 5.5 describes the task and techniques associated with every stage of the developed novel LeanKLC; these being knowledge identification, knowledge capture, knowledge representation, knowledge sharing, knowledge integration and knowledge use and provision. Lastly, Section 5.6 provides a reflection on how to manage the entire LeanKLC framework.

5.2 Baseline Model – Three Dimensions of Knowledge Management in Product Development

Developing a baseline model in the form of three dimensions of knowledge management in product development was regarded as vital due to two main reasons. Firstly, it aims to provide a product development centric research foundation for the development of the LeanKLC. Secondly, it is necessary to display where knowledge is located and how it relates within the scope of a product development process. This intends to increase product designers' and engineers' awareness of apparent knowledge flow and address its related challenge, as reported in Section 4.4.2. Although a product development process consists of several phases (Ulrich and Eppinger, 2008) its definition, sequence and amount differ among companies. Consequently, in this section, the baseline model is explained on a schematic product development process, as illustrated in Figure 5.2, which consists of four phases, namely concept, detail design, testing and production.

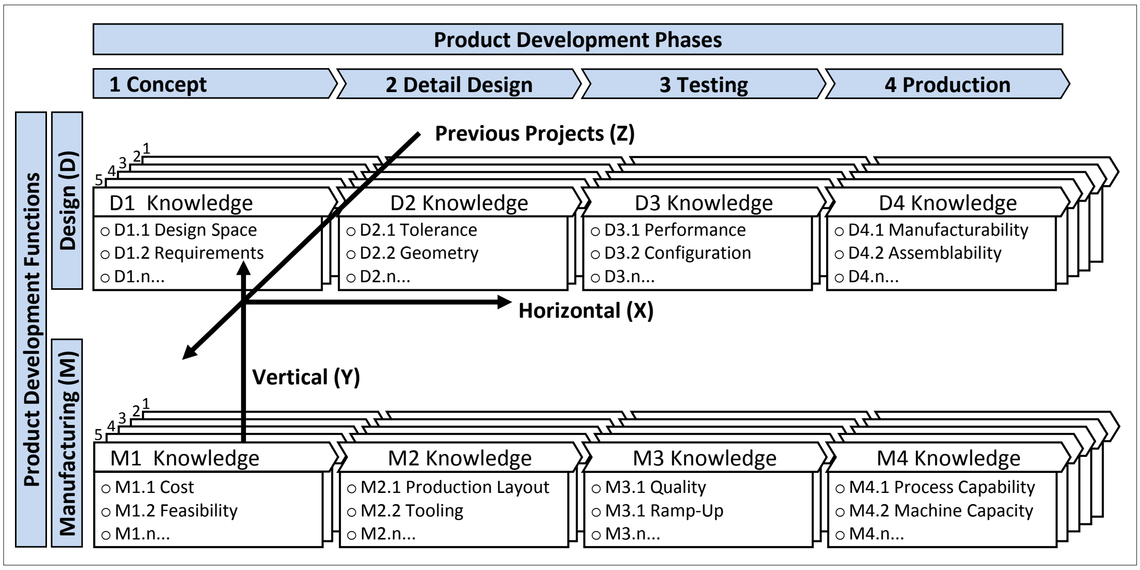


Figure 5.2 Baseline Model - Three Dimensions of Knowledge Management in Product Development

These phases comprise several activities, which are undertaken within the different business functions in an organisation, such as Manufacturing (M) and Design (D). In the industrial field study, presented in Section 4.3, engineers stated that in-house created sources of knowledge are most important. By itself it is important to understand that specific knowledge is created within every phase and function. For example, knowledge related to design space is created in the design (D) function during the concept phase (D1), illustrated in Figure 5.2 as D1.1. Process capability M4.1 and machine capacity M4.2 knowledge on the other hand, is created in the manufacturing (M) function during the production phase (M4). Consequently it is possible to locate specific knowledge within every phase and function that has a particular contribution to the product development process. However, the industrial field study, presented in Section 4.3, also indicated that over 70% of a product design is based on knowledge from previous projects, meaning that such knowledge was correspondingly created during product development undertaken in the past. Consequently, it is again possible to contextualise knowledge in product development within three dimensions, namely horizontal (X), vertical (Y) and previous projects (Z), as illustrated in Figure 5.2.

Horizontal dimension (X) symbolises that knowledge is required to sequentially proceed in the product development process. For example, in the design (D) function the knowledge acquired in the concept (D1) phase, such as new customer requirements (D1.2), is provided to the detail design team in order for it to be realised in the new design.

Vertical dimension (Y) exemplifies that knowledge needs to be obtained or shared within other functions in the product development process. This can include sharing knowledge concurrently between the manufacturing (M) and design (D) function during the concept phase in order to assure that manufacturing feasibility (M1.2) is considered at an early stage of the product design process.

Previous projects dimension (Z) embodies knowledge a company has acquired in the past. For instance, during testing (D3) in the design (D) function, the product development engineer retrieves proven test configurations (D3.2) from previous projects in order to initiate the validation process.

Given the above, the three dimensions are contextualised and provide the baseline model in the form of three dimensional Cartesian coordinates, as shown in Figure 5.2. Hence, this research refers to the baseline model in addition to the three dimensions of knowledge management in product development with the perspective of Cartesian coordinates and the process of product development. The baseline model will guide the development of the LeanKLC; in particular providing the rationale for knowledge capture seen in Section 5.5.2 and knowledge representation in Section 5.5.3. Moreover in respect to this research, the three dimensions of knowledge management are contextualised to lean product development and explained in the following section.

5.3 Contextualising the Three Dimensions of Knowledge Management with Lean Product Development Process Models

The previously described baseline model, entitled three dimensions of knowledge management in product development, was contextualised on a schematic product development process in order to manifest its definition. However, the core process of any lean product development is set based concurrent engineering. Moreover, 'lean product development is product development in a knowledge environment' as stated by Al-Ashaab et al. (2010). For this reason this section presents the relation of the three dimensions of knowledge management in product development within the context of set based concurrent engineering.

Therefore, four acclaimed lean product development process models, Ward et al. (1995), Sobek et al. (1999), Kennedy et al. (2008) and Khan (2012) are mapped against the three dimensions of knowledge management in product development in order to present the role of knowledge in such an environment as illustrated in Figure 5.3. The acclaimed lean product development processes models shown in Figure 5.3 are all conceptual, apart of Khan (2012) which is one of the main outputs of the LeanPPD project. For example, Ward et al. (1995) uses only a hand written sketch from a body engineer at Toyota. Nevertheless, mapping the three dimensions of knowledge management against the LeanPD process models indicates that the design of their process influences knowledge flow to support product development. Although these process models raise the importance of knowledge, none of them define a clear knowledge flow definition to support the full implementation of LeanPPD. Therefore, the contribution to the described gap is presented in this thesis.

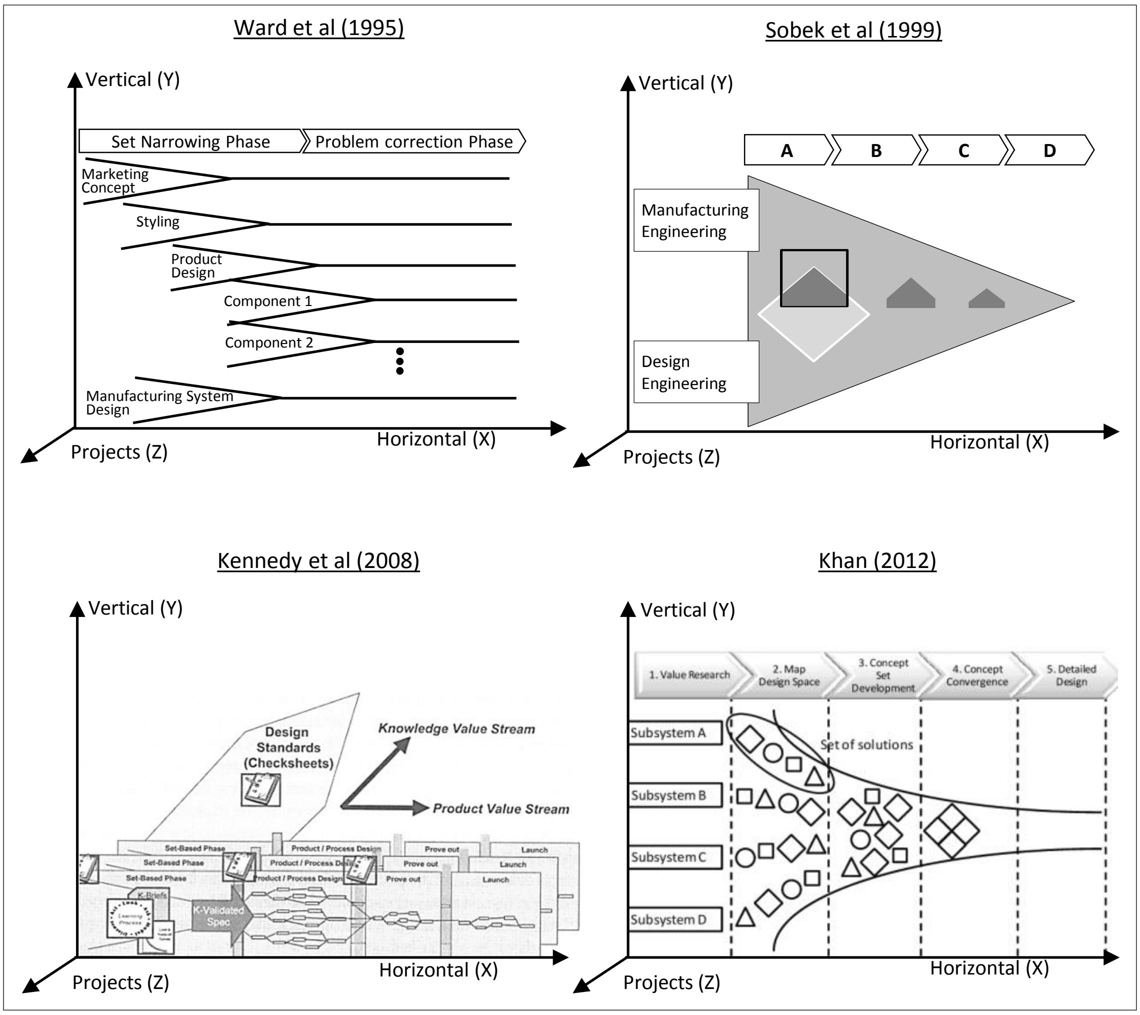


Figure 5.3 Contextualising the Knowledge Environment in Lean Product Development

Table 5.1 details the contextualisation of horizontal (X), vertical (Y) and projects (Z) dimension within the LeanPD process models. Kennedy et al. (2008) is the only LeanPD process model which conceptualises the projects (Z) dimension defined as knowledge value stream based on parallel running life projects.

On the other hand, all four LeanPD process models place emphasis on the knowledge flow in (X) direction, i.e. sequential knowledge sharing between PD phases or activities. This is where the main consideration to generate alternative design solutions as well as advancing during the set narrowing process takes place.

Table 5.1 Contextualising Three Dimensions of Knowledge Management with LeanPD Process Models

LeanPD Model	Horizontal (X)	Vertical (Y)	Projects (Z)
Ward et al. (1995)	- Set Narrowing Phase - Problem-Correction Phase	- Marketing Concept - Styling - Product Design - Component 1 - Component 2 - Component n - Manufacturing System Design	-
Sobek et al. (1999)	- Map Design Space - Integration - Set Narrowing - Convergence	- Design Engineering - Manufacturing Engineering	-
Kennedy et al. (2008)	- Product Value Stream - Set Based Phase - Product / Process Design - Prove Out - Launch	-	- Knowledge Value Stream (in form Design Standards, e.g. Check Sheets)
Khan (2012)	- Value Research - Map Design Space - Concept Set Development - Concept Convergence - Detail Design	- Subsystem A - Subsystem B - Subsystem C - Subsystem n	-

With regard to the vertical (Y) dimension two conditions are relevant in the case of lean product development. The first condition corresponds to the vertical (Y) dimension as the sharing of knowledge between two functions (e.g. design and manufacturing) which is equivalent to the term ‘convergence’, as defined by Sobek et al. (1999) when supporting each other’s decision.

Subsequently, during set narrowing a second condition of vertical (Y) dimension is apparent, which is the knowledge sharing between different design solutions. This takes place when knowledge is shared vertically (Y) among either component (Ward et al., 1995) or subsystem (Khan, 2012) levels in advance of set narrowing. Khan (2012) emphasises the importance of knowledge sharing among the definition of subsystems in order to achieve easy integration of these solutions in order to generate the alternative system solutions. The combinations of subsystems consequently results in one full product system. Given the above, this research defines set narrowing as a combination of knowledge sharing between different design solutions in vertical (Y) dimension and the sequential sharing of resulting knowledge in horizontal (X) dimension to the proceeding activity of set narrowing. This set narrowing process is conceptualised in Figure 5.4 using an example of four potential design solutions initiated for the first set narrowing activity.

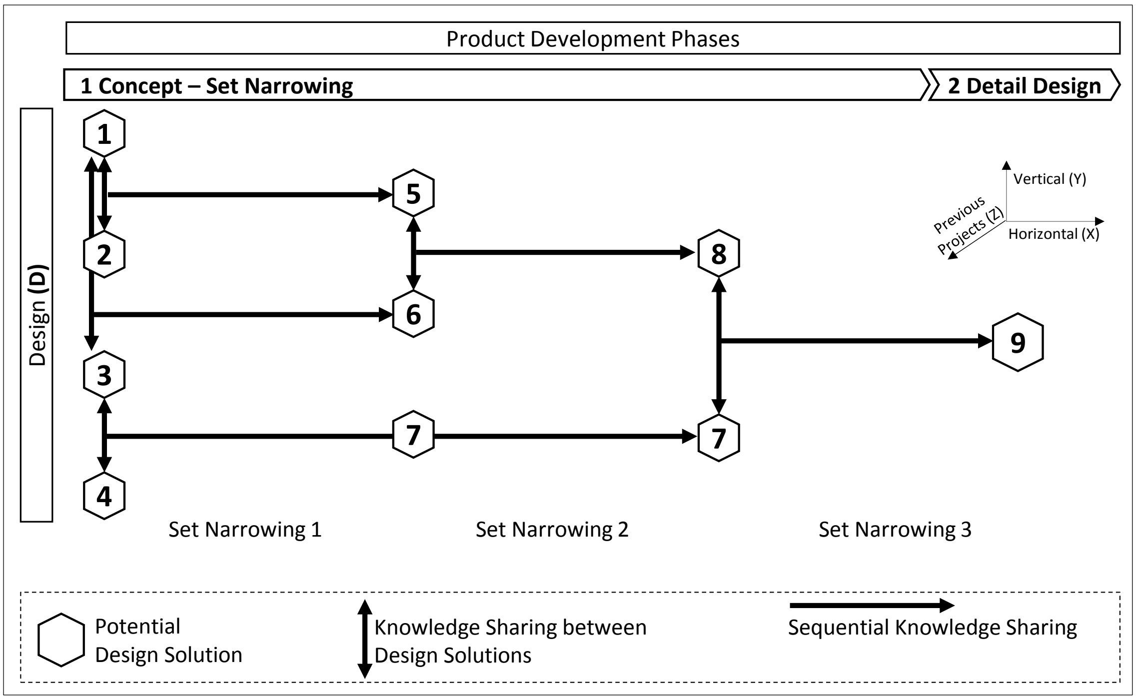


Figure 5.4 Concept of Set Narrowing by Sharing Knowledge in Vertical and Horizontal Dimension

Figure 5.4 shows that vertical knowledge sharing is possible between any of the potential design solutions. For example, potential design solutions 5 and 6 both originate from potential design solution 1. It is also possible that a design solution passes a set narrowing activity if no better alternative is found, as illustrated with potential design solution 7. Overall, the example in Figure 5.4 shows that 8 different design solutions have been narrowed down by sharing knowledge in vertical (Y) and horizontal (X) dimensions to reach a final design, as illustrated with design solution 9.

While the horizontal (X) and vertical (Y) dimensions of the baseline model found a contextualisation with existing lean product development process models, the projects (Z) dimension provide a major gap, which therefore encompasses special attention for the development of the LeanKLC. In particular, the consideration that in LeanPD no key decision should be made until sufficient knowledge is demonstrated (Al-Ashaab et al., 2010) justifies the significance of the three dimensions of knowledge management to provide a wider knowledge environment that will support key decision taking from different angles as well as provide further definition for set narrowing. Hence, the following section describes the LeanKLC stages that have been defined accordingly.

5.4 Synthesising LeanKLC Stages for a Lean Product Development Knowledge Environment

Previous Sections 5.2 and 5.3 intended to increase the understanding of knowledge management in product development and provided a related baseline model. A knowledge life cycle entails key stages with incorporate techniques arranged in a logical connection (refer to Section 3.5). However, the literature review outlined a gap, see Section 3.7, that currently there is no suitable knowledge life cycle to support lean product development. This section presents the argument regarding the key stages required to support lean thinking application.

Although synthesising two different disciplines, namely product development and knowledge management, encounters increased complexity, it was evident during the literature review in Chapter 3 that there are several intersections as well as points of interest. On the other hand, the presented industrial challenges in Section 4.4 outlined that there is less sympathy between the two disciplines among product designers and engineers as was initially expected. Due to the immense presence of industrial challenges, the author believes that it embodies the main focus point for the definition of LeanKLC stages.

For this reason, the LeanKLC stages that will be addressed in this research are identified during the industrial challenges classification in Section 4.4. With respect to the top stream of knowledge life cycle concerns these are knowledge capturing, knowledge sharing and knowledge use and provision. Originally defined as two categories during challenge classification, knowledge use and provision are merged into one stage; hence, both describe perspectives of getting the captured knowledge to the stakeholders. From the top stream of challenges related to product development environment the author defined integration as another stage of the LeanKLC to be addressed in this research due to the ever increasing product data as well as demand of supportive IT technologies.

Two more LeanKLC stages are depicted as a result of the literature review. First, knowledge identification was concluded as a vital stage in order to capture useful knowledge. Moreover, the industrial challenge of capturing the right content, which in fact was the most frequently raised industrial challenge in Section 4.4, is largely dependent on accurate knowledge identification. Secondly, knowledge representation was selected due to the capability of enhancing the visualisation as well as easing computational use of the captured knowledge. Given the above, the LeanKLC stages addressed in this research are in the following sequential order:

1. Knowledge Identification
2. Knowledge Capturing
3. Knowledge Representation
4. Knowledge Sharing
5. Knowledge Integration
6. Knowledge Use and Provision

Once the LeanKLC stages are depicted, the next step comprises the synthesising of the knowledge environment discussed in the lean product development literature and reviewed in Section 3.3. Accordingly, Table 5.2 illustrates the potential link of tools and techniques as currently discussed in the LeanPD literature in supporting the stages of the LeanKLC and indicated with a circle symbol. A special emphasis has to be made on the words “potential link”, hence the tools and techniques have not been addressed yet in this context and were not originally developed to support a knowledge life cycle. Table 5.2 also shows those linkages that have been addressed during this research to as part of the LeanKLC development and indicated with letter X.

For instance, formal representation of product development knowledge has not yet been discussed in the lean product development community; hence its influence on this research is guided from the knowledge management discipline as well as on the findings from industrial collaboration. Knowledge integration could be potentially linked within the context of centralised knowledge, in particular know-how database and the essence of standardised processes, as well as the captured knowledge.

Potential tools for knowledge identification could be product development value stream mapping, or 5Whys in combination with the A3 Template and Report. Knowledge capturing incorporates several possibilities of departure. These could be focusing on already documented knowledge in concept papers and design notebooks, structuring and storing knowledge in a know-how database or designing a process to capture test-then-design knowledge, just to mention a few.

Table 5.2 Potential Link of Knowledge Environment Tools and Techniques with LeanKLC Stages

Knowledge Environment in Lean PD Literature from Chapter 3 Area of Discussion	Tools and Techniques	Key KLC Stages depict from Chapter 3 and 4 Knowledge Identification	Knowledge Capture	Knowledge Representation	Knowledge Sharing	Knowledge Integration	Knowledge Use and Provision
Decision Making							
	Check Lists / Check Sheets						ⓧ
	Chief Engineer				○		
	Integration Events				○		○
	Ringi System (Formal Decision Making Process)				○		
	Test then design (Ijiwary)		○				
	Concept Paper		○				
	Decision Matrix						○
	Design Notebooks		○				○
Centralised Knowledge							
	Know-How Database		ⓧ			ⓧ	
	Standardisation (Process, Knowledge)		ⓧ			ⓧ	
	Knowledge Pull						○
	Lessons Learnt						○
	Design History						○
	Competitor Tear Down Analysis Sheets		○				○
	Benchmark Reports - Best Practices		○				○
Visualisation							
	Trade-Off Curves[1]	X	X	X	ⓧ		ⓧ
	Visual Management (Jidoka)				ⓧ		
	Visual Project Board				○		
	Health Chart				○		
	Product Development Value Stream Mapping	○					
Problem Solving							
	A3 Template and Report[1]	ⓧ	ⓧ	X	ⓧ	X	ⓧ
	LAMDA (Look, Ask, Model, Discuss, Act)	X	X		ⓧ		
	PDCA (Plan, Do, Check, Act)				○		
	5 Whys	ⓧ					
	Continuous Improvement (Kaizen)				ⓧ		
	Open Office Culture (Obeya)				ⓧ		
	Reflection Events (Hansei)				○		
	Group Problem Solving (Nemawashi)				ⓧ		
	Multifunctional Teams				○		

○ Potential linkage to a KLC stage according to current discussion in LeanPD literature

X Addressed in this chapter and linked to particular LeanKLC stage

ⓧ Both the above

Knowledge sharing and knowledge use and provision comprise the stage with the highest number of potential linkages. However, this shows that the lean product

[1] Primary focus of the work presented thesis and research.

development literature neglected the detail of knowledge capturing. For example, although trade-off curves have been linked with the potential to share and re-use knowledge, the knowledge needs to be captured in the first place, of which detail is not provided. As such, this research is developing the missing link in the form of a LeanKLC.

On the other hand, linking in detail the entire listed tools and techniques, as illustrated in Table 5.2, would result in a scope that goes beyond one individual research project. Therefore, this research will have a primary focus on synthesising trade-off curves and A3 thinking. This is accomplished by demonstrating the application of the LeanKLC stages in two distinguished streams related to the development of A3 thinking to support problem solving and the development of trade-off curves to support set based design at the conceptual stage. Hence, the LeanKLC is used to enhance current applications of trade-off curves and A3 thinking to realise increased potential during lean product development.

5.4.1 Application of LeanKLC Stages to Develop A3 Thinking for Problem Solving

The application of the LeanKLC stages to develop A3 thinking for problem solving was chosen due to the agreed hypothesis that product development is an ever repeating problem solving activity. This hypothesis is also supported by the industrial field study where engineers expressed that 79% of all design problems could have been prevented by the correct knowledge being provided, as seen in Section 4.3.

However, adapting a traditional A3 template, as illustrated in Figure 3.7 (Section 3.3.4), is particularly challenging as its approach was originally developed for the manufacturing environment. For this reason, the author used the LeanKLC to enhance the newly developed A3 template called A3LAMDA, developed by Mohd-Saad et al. (2013). The A3LAMDA template combines for the first time LAMDA learning cycles with A3 problem solving, hence providing a problem solving approach suitable for product development. During industrial interaction the author integrated key stages of the LeanKLC in certain elements of the A3LAMDA template. In addition, the work resulted in excluding and merging certain elements of the original A3LAMDA template.

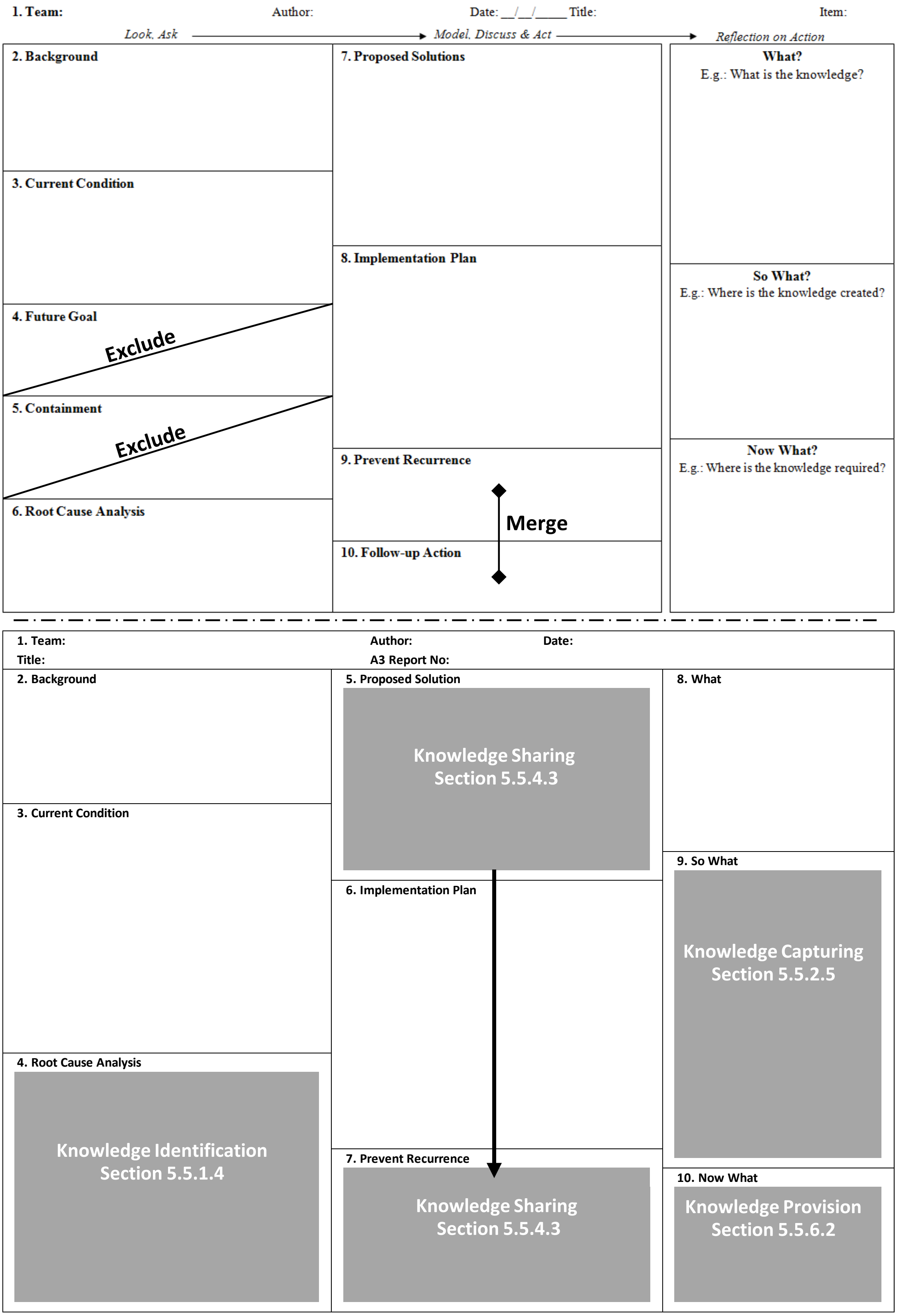


Figure 5.5 Top – First Version of A3LAMDA Template developed by Mohd-Saad (2013), Bottom – Elements of A3LAMDA Template including LeanKLC Enhancement

As illustrated in Figure 5.5, the first version of the A3LAMDA template developed by Mohd-Saad (2013) consists of 13 elements. However, the author decided to exclude two elements of the original A3LAMDA template, namely future goal and containment, and to merge the elements of prevent reoccurrence and follow up action into one. As a result, the adapted version consists of ten elements, three less than the original, due to the following reasons.

Excluding the future goal element was undertaken due the fact that it is largely evident in product development that designers are concerned to develop products that fulfil customer specifications. Hence, documenting the exact customer specification in the background element of the A3LAMDA template will provide enough information and logic about the future goal. A similar reason is the exclusion of the containment element. There are different containment options in the form of design verification or validation processes, which are very well understood amongst product designers and engineers. For example, the documentation of the test request number in the current condition element will provide enough information about the necessary containment action required.

The merger of prevent reoccurrence and follow-up element, as shown in Figure 5.5, was conducted because a straight relation between the two elements was identified and therefore represented in one element. Excluding and merging certain elements of the original A3LMADA template was the first step in order not to force designers and engineers to document unnecessary or duplicate information and therefore increase the probability of commitment, a human factor challenge reported in Section 4.4.2.

The newly developed LeanKLC in this research provides the means to support the following key elements of the A3LAMDA solving the product design problem, which itself means creating new knowledge.

Figure 5.5 illustrates how the different key stages of the LeanKLC are employed to support the different elements of the A3LAMDA. This will be explained in detail in the following sections. In brief, the knowledge identification stage to support the work of root cause analysis of the identified product design problem is presented in Section 5.5.1.4. Dynamic knowledge capture as part of element number 9 (so what) is explained in Section 5.5.2.5. Knowledge sharing with regard to supporting the current problem solving activity in element number 5 (proposed solution) as well as the sharing of resulting effective design solutions in element number 7 (prevent recurrence) is explained in Section 5.5.4.3. Finally, element number 10 (now what) is concerned with the declaration of where the knowledge is needed in future within the context of three dimensions of knowledge management in product development and presented in Section 5.5.6.2.

5.4.2 Application of LeanKLC Stages to Develop Trade-off Curves in Set Based Design

Trade-off curves as another application of the LeanKLC was selected due to the apparent complex product development environment in which designers and engineers expressed a need for simple but technically relevant tools. However, as opposed to multi objective design optimization, a discipline where trade-off curves are commonly used, this research will tolerate a conflict between different objectives. On the contrary, the author believes that such conflicts encourage the consideration of multiple design solutions as required in set based concurrent engineering and illustrated in Figure 5.4.

Hence, this research focuses on visually displaying knowledge using trade-off curves in order to support engineering decision taking in lean product development, which in return requires a sequence of knowledge life cycle stages. The LeanKLC stages adapted to develop trade-off curves in the scope of this research include knowledge identification with regard to defining main decision criteria (Section 5.5.1.5), knowledge capturing based on decision criteria using different types of trade-off curves (Section 5.5.2.3), a knowledge representation concept using UML class diagram (Section 5.5.3.3), knowledge sharing through visualisation (Section 5.5.4.3), as well as knowledge use and provision during the set narrowing phase (Section 5.5.6.1). The next section involves the sequential arrangement and the description of supporting tasks and techniques of the novel LeanKLC.

5.5 Definition of novel LeanKLC Framework to support Lean Product Development

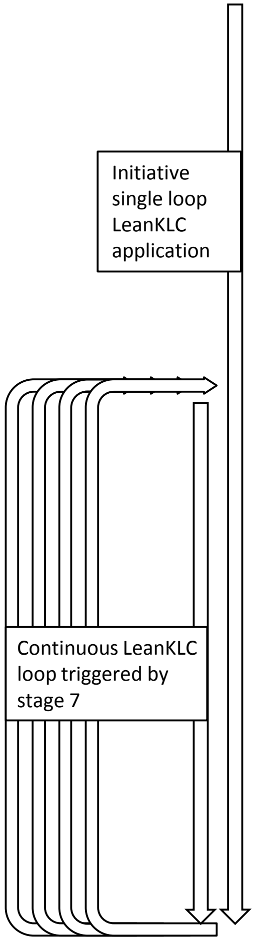
This section presents one of the core contributions of work presented research, this being the definition of novel LeanKLC framework to support LeanPD. Table 5.3 illustrates the LeanKLC framework including sequence of stages (as explained in Section 5.4), tasks, streams as well as related section numbers. The presented novel LeanKLC is a generic framework that could be used in any sector or project. Its intention is to have a systematic approach to manage product development related knowledge to support a thorough LeanPD implementation. For this reason, the presented explanations of each stage and its related tasks are recommendation guidelines to be followed and then adapted and modified according to the needs of the company.

Particular applications of the LeanKLC are demonstrated in two streams, these are problem solving using A3LAMDA and development of trade-off curves. The fields with a cross in Table 5.3, refer to the use of task and related techniques in order to demonstrate the application of the LeanKLC within these streams. This style of distinguishing between the two LeanKLC is used throughout the thesis.

Initiating a LeanKLC application comprises the single loop accomplishment of stages 1-7 in sequential order, as shown in Table 5.3. The first two stages (1 and 2) address the identification of existing and the capturing of previous knowledge. Stages 3, 4, 5 and 6 on the other hand are building a continuous knowledge life cycle loop triggered by stage 7, which is dynamic knowledge capturing during the actual design and development of a product. Accordingly two stages for knowledge capturing exist, namely previous knowledge capture in stage 2 and dynamic knowledge capture in stage 7, its rationale being explained in Section 5.5.2.

The following subsections present in a level of detail the meaning and suggested techniques to be employed in order to carry out the application of each stage in the novel LeanKLC. However, companies are advised to carefully choose a well-defined tailored set of tasks and techniques best suitable for the operating environment and area of LeanKLC implementation. In fact, the stage of knowledge identification helps to provide the path for such customization and is explained in the following subsection.

Table 5.3 The LeanKLC Framework: Stages, Tasks and Streams



Lean Knowledge Life Cycle Stages	Tasks	Tasks supporting LeanKLC stream		Section Number
		A3LAMDA	Trade-off Curves	
1.Knowledge Identification	1.1 Increase Awareness in LeanKLC Management			5.5.1.1
	1.2 Identify useful Knowledge			5.5.1.2
	1.3 Map the Process with Knowledge intensive LeanPD Activities			5.5.1.3
	1.4 Integrate Knowledge Identification in A3LAMDA Template	X		5.5.1.4
	1.5 Identify Decision Criteria to develop Trade-off Curves		X	5.5.1.5
2. Previous Knowledge Capture	2.1 Structure identified Knowledge			5.5.2.1
	2.2 Capture identified Previous Knowledge			5.5.2.2
	2.3 Capture Trade-Off Knowledge		X	5.5.2.3
3. Knowledge Representation	3.1 Define Key Knowledge Attributes	X		5.5.3.1
	3.2 Graphically Represent Knowledge Provision	X		5.5.3.2
	3.3 Formally Represent Captured Knowledge		X	5.5.3.3
4. Knowledge Sharing	4.1 Centralise Knowledge and Appoint Knowledge Owners			5.5.4.1
	4.2 Facilitate Knowledge Sharing			5.5.4.2
	4.3 Share Knowledge through Visualisation	X	X	5.5.4.3
5. Knowledge Integration	5.1 Gather Functional Requirements			5.5.5.1
	5.2 Adapt a System Architecture	X		5.5.5.2
	5.3 Integrate Knowledge in a Centralised Knowledge Base	X		5.5.5.3
	5.4 Integrate Knowledge in the Product Development Process	X		5.5.5.4
6. Knowledge Use and Provision	6.1 Use Trade-off Knowledge during Set Narrowing Phase		X	5.5.6.1
	6.2 Establish a Mechanism that Supports Knowledge Provision	X		5.5.6.2
	6.3 Provide Useful Knowledge at the Right Time and Place	X		5.5.6.3
7. Dynamic Knowledge Capture	7.1 Explore ways of Dynamic Knowledge Capture for the LeanPD Knowledge Environment			5.5.2.4
	7.2 Dynamically Capture Knowledge during Problem Solving using A3LAMDA Template	X		5.5.2.5

5.5.1 Knowledge Identification: Stage1 of the LeanKLC

The stage of knowledge identification aims to localise and identify the useful knowledge that a company has and needs. It is the first stage of the LeanKLC and therefore provides the basis for the following stages. Consequently, the level of accuracy within this stage significantly affects the performance of the entire LeanKLC applications. In fact, initial knowledge identification is time intensive and requires engagement and active interaction with product development personnel.

Table 5.4 Knowledge Identification: Key Tasks and Techniques

Lean Knowledge Life Cycle Stages	Tasks └─Techniques (if applicable)	Tasks supporting LeanKLC stream	
		A3LAMDA	Trade-off Curves
1. Knowledge Identification	1.1 Increase Awareness in LeanKLC Management 1.1.1 Industrial Workshop via Focus Group		
	1.2 Identify useful Knowledge 1.2.1 Questionnaire		
	1.3 Map the Process with Knowledge intensive LeanPD Activities 1.3.1 Work Flow Diagram		
	1.4 Integrate Knowledge Identification in A3LAMDA Template 1.5.1 Root Cause Analysis	X	
	1.5 Identify Decision Criteria to develop Trade-off Curves 1.6.1 Pairwise Comparison Matrix		X
2. Previous Knowledge Capture			
3. Knowledge Representation			
4. Knowledge Sharing			
5. Knowledge Integration			
6. Knowledge Use and Provision			
7. Dynamic Knowledge Capture			

Table 5.4 illustrates the defined tasks and techniques during the stage of knowledge identification. The tasks are described in the following subsections which include: increase awareness in LeanKLC management in task 1.1, identify useful knowledge in task 1.2, map the process with knowledge intensive LeanPD activities in task 1.3, integrate knowledge identification in A3LAMDA template in task 1.4 and identify decision criteria to develop trade-off curves in task 1.5.

5.5.1.1 Increase Awareness in LeanKLC Management

The knowledge environment is a key enabler of the lean product and process development model (Al-Ashaab, 2012). However, the human factor challenge of ‘awareness’ (Section 4.4.2) provided evidence that key principles of knowledge management are under-represented in current product development applications. Accordingly, this task aims to equip product designers and engineers with a broader understanding of the importance and challenges in managing product development knowledge as well as showcasing potential applications of the LeanKLC.

During this research, the conduct of industrial workshops via focus groups was experienced as effective in accomplishing this task, hence it provides a setting of active interaction among future stakeholders. The method of focus group is described in Section 2.3.3.1. In reality this task requires the conduct of several industrial workshops with key stakeholders in order to define the following:

- a need to apply the proposed novel LeanKLC in order to support product development realisation in lean environment
- scope and objectives for the LeanKLC initiative
- capturing the stakeholder requirement of the envisioned knowledge environment to support LeanPPD
- project plan and allocation of human resources to realise the above

With the intention of achieving a successful knowledge management initiative, the increase awareness task is essential to make sure that key stakeholders believe in the fact that the product development process will be significantly enhanced by the adaption and application of the proposed novel LeanKLC to provide the adequate knowledge environment and moreover that such adaption requires commitment.

5.5.1.2 Identify useful Knowledge

Previous research outlined both the need and a lack of method to identify knowledge in product development (Salisbury, 2008; Baxter et al., 2009; Liker and Morgan, 2011). In fact, defining the adequate ‘content’ prior to knowledge capturing was the most frequently raised challenge in managing product developed knowledge during empirical data collection, as explained in Section 4.4.1. Hence, the location of useful knowledge is vital and suggested using questionnaires in order to provide direction regarding adequate content for knowledge capturing. Accordingly, this subsection offers guidance on appropriate questionnaire design as well as indicators for useful knowledge, as explained below.

5.5.1.2.1 Questionnaire Design

This subsection provides guidance resulting from industrial field research, as presented in Chapter 4, for designing appropriate forms of questions. The author realised that two criteria are particularly important for question design in order to obtain meaningful data; these are time commitment for each participant and overall number of participants available, as shown in Figure 5.6.

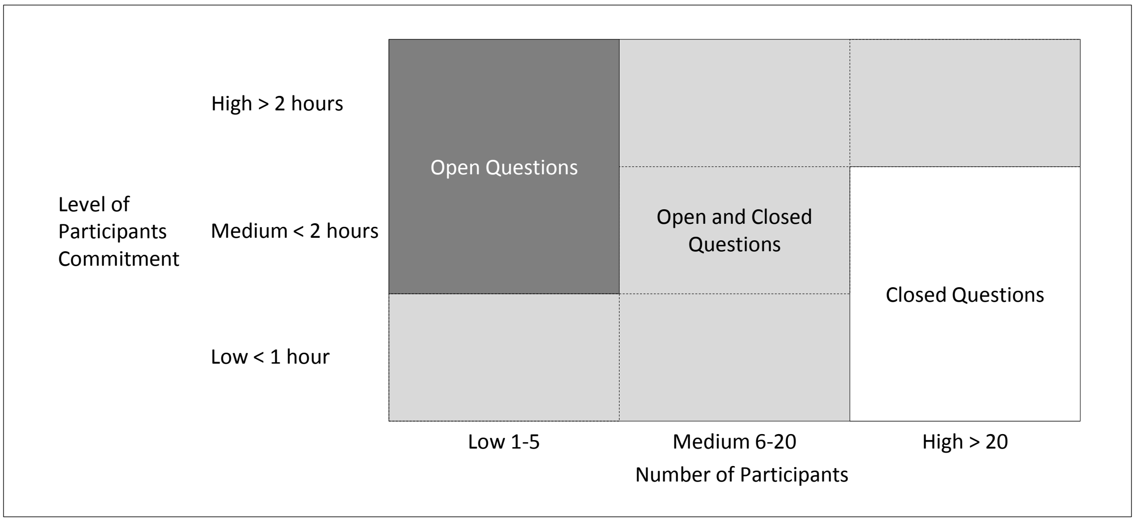


Figure 5.6 Suggested Form of Questions based on Participants Availability

Open questions are suggested when the number of participants is low and the time commitment is medium to high. The reason for this is that the approach is time consuming and requires thorough investigation of collected feedback, although it does provide real insights from key informants due to the informal nature of the approach.

Closed questions on the other hand, are suggested when the number of participants is high and the level of time commitment low to medium. The low time constraint indicates the necessity for specific questioning. High levels of participation mean that quantitative data can be collected and analysed to make sufficient statements with regards to multiple choice, rating or ranking questions.

The use of structured as well as open questions could provide mixed benefits, although requires balancing between time constraint for open questions as well as number of participants in order to conclude sufficient statements from closed questions. Hence, defining an adequate form of questions is vital. Of likewise importance is the rationale and content of the questioning. For this reason, it is suggested that two main elements of knowledge identification using questionnaires are addressed:

1. **Identify what knowledge does the product designer or engineer need.**
   1.1. Formulate question with regards to sources of knowledge
   (e.g. *'Where are product design rules currently available in your company?'*)
      1.1.1. Open / closed
   1.2. Formulate question with regard to preferable form of knowledge
      1.2.1. Open / closed
   1.3. …continue until scope of LeanKLC application is covered with regard to what knowledge does the product designer or engineer need.

2. **Identify where does knowledge exist and how it was captured before.**
   2.1. Formulate question with regard to current knowledge formats
      2.1.1. Open / closed
   2.2. Formulate question with regard to knowledge sharing
      2.2.1. Open / closed
   2.3. …continue until scope of LeanKLC application is covered with regard to where does knowledge exist and how it was captured before.

Although both main elements require consideration during knowledge identification, the specific formulation of questions is relative to the scope of LeanKLC application. For example, a product design engineer relies on design rules as a source of knowledge. Hence, a question that addresses sources of knowledge could be formulated: 'Where are product design rules currently available in your company?' Consequently, the product design engineer would point out that the design rules are not documented in the available design manual or outline and that engineers rely on tacit knowledge.

5.5.1.2.2 Indicators for useful Knowledge

Once questionnaires are completed, the entire knowledge identified is not always useful to the engineers. During industrial challenge classification (Section 4.4) that resulted from direct interaction with product designers and engineers the following indicators for useful knowledge identification were concluded by the author.

- Obsolescence[2]: knowledge is valid and not out of date.
- Replacement[2]: knowledge is not replaced by another.
- Accuracy[2]: knowledge is defined in a detailed, distinctive and unmistakeable format.
- Trust Factor[3]: knowledge content and source are reliable.
- Compatibility[4]: the knowledge format is compatible within the company's infrastructure.

Another aspect is to analyse repetitions of identified knowledge in order to recognize either interrelations among the different knowledge sources or unnecessary duplication of knowledge. Finally, the above indicators are used to guide the extraction of useful as well as elimination of not useful knowledge during identification.

5.5.1.3 Map the Process with Knowledge intensive LeanPD Activities

As outlined in research gap 2 (Section 3.7), the LeanKLC aims to assist in the creation of a knowledge environment to support lean product development. Consequently, companies applying the LeanKLC undergo a process of improving the current product development process. Therefore, this task provides a snap shot of the current knowledge flow in product development (As-Is), as well as creating a conceptual future state (To-Be) of the envisioned knowledge environment. It is particularly important to map knowledge intensive activities where key decisions are made or a large quantity of knowledge is needed or created.

The use of work flow diagrams is suggested to accomplish this task as it illustrates the product development process and key activities in a visual way and therefore provides a communication medium to smoothly interact with product development engineers. Moreover, due to the complex nature of the product development process, the work flow diagram offers the flexibility to create customised objects to visually reproduce the process map in the most realistic way. Alternatively, this task can also be accomplished using process mapping tools such as IDEF0 or product development value stream mapping.

Sources of Evidence
[2] Knowledge capture - content challenge section 4.4.1.1.
[3] Human factors - responsibility challenge section 4.4.2.3.
[4] Integration - format challenge section 4.4.2.2.

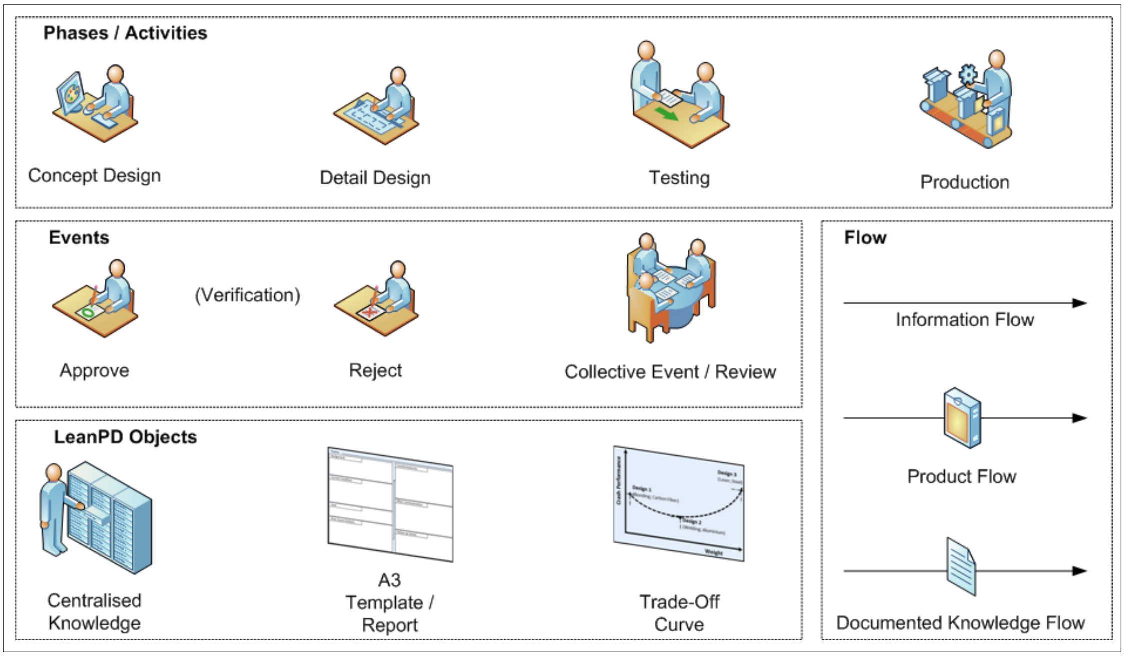


Figure 5.7 Selected Work Flow Diagram Objects for mapping the envisioned LeanPD Knowledge Environment

Figure 5.7 shows a selection of work flow diagram objects used and developed during this research to identify knowledge intensive activities. It comprises objects that represent phases or activities, events, flow and most important objects related to the lean product development knowledge environment, such as A3 template or trade-off curve.

5.5.1.4 Integrate Knowledge Identification in A3LAMDA Template

Identifying useful knowledge accelerates finding a solution by reducing the number of iterations during problem solving, as illustrated in Figure 3.6 (Section 3.3.4). Therefore, the knowledge identification capabilities during root cause analysis in A3LAMDA element number 4 have been enhanced with a newly developed version of the cause and effect diagram, also called fishbone. The enhancement comprises the modifications in two aspects, which are explained as follows.

Firstly, the traditional cause and effect diagram, as shown in Figure 5.8, requires the problem solving team to define potential causes. This however, can be time consuming and is therefore likely to demotivate engineers if the potential causes are not evident. Instead it is suggested to determine the most potential root cause categories upfront in the form of apparent product design issues, as shown in Figure 5.8, in order to guide the problem solving team as to where useful knowledge can be located.

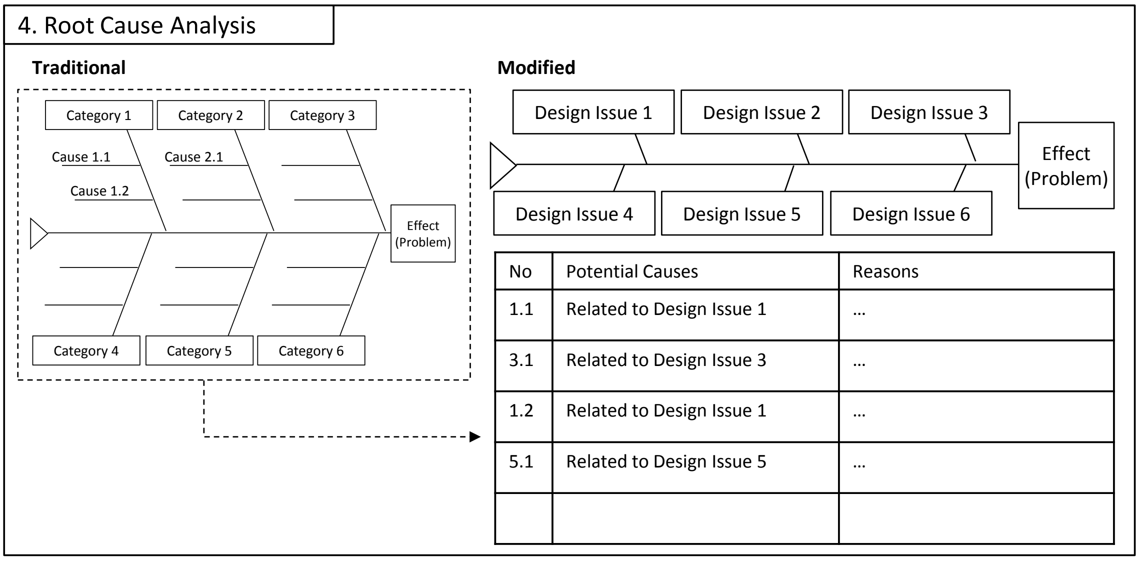


Figure 5.8 Modified Root Cause Analysis to enhance Knowledge Identification

Secondly, the shape of the original fishbone diagram was changed in order to provide evidence about the history of knowledge identification activities during root cause analysis. Hence, the modified fishbone diagram has no more separate lines for each root cause, instead it provides a table where the problem solving team documents potential design issues in chronological order. As shown in Figure 5.8 for example, the problem solving team may consider in the first place design issue 1 as the cause of a failure, once knowledge was identified and used it was seen as a less possible root cause. The second thought tended towards design issue 3, the third back towards design issue 1, until finally in the fourth attempt the root cause was found at design issue 5. Inserting a table below the modified fishbone diagram will first of all eliminate duplicate knowledge identification activities, but more importantly provide evidence for future reference about the sequence of finding a root cause.

As such, the numbering in the modified fishbone diagram (Figure 5.8) firstly represents the number related to the design issues and secondly the order of investigating different root causes within the same issue. For example, the number 1.2 in the table means that the potential root cause relates to design issue 1 and that it was the second root cause investigated. Also, the possibility of having increased the space of documentation as opposed to the traditional fishbone, will give the problem solving team chance to investigate the root cause in more detail. Arguably the visualisation aspect decreased with the new adopted fishbone technique; however, this was taken into account due to the mentioned advantages but also with regard to the limited space available in the element of an A3LAMDA template.

5.5.1.5 Identify Decision Criteria to develop Trade-off Curves

The decision making in product development as investigated during empirical research, comprises trade-off between certain decision criteria based on customer requirements in order to propose a complying design solution. However, such trade-off is largely accomplished by engineers using their own tacit knowledge. In addition, some criteria are more important than others in certain stages of the product development process.

For these reasons, the author suggests pairwise comparison as applied in the analytical hierarchy process for determining priorities among decision criteria, as developed by Saaty (1980). This aims to identify the most important decision criteria in order to create adequate trade-off curves that support decision making in LeanPD. Pairwise comparison also found application in the KLC of Firestone and McElroy (2003) to determine ratio scales for knowledge claim evaluation criteria. Pairwise comparison however, requires the identification of decision criteria as encountered by key informants, accordingly the author suggest following steps:

1. Put forward several decision criteria resulting from questionnaire conduct as explained in Section 5.5.1.2.
2. Allow key informants to verify decision criteria
3. Create a pairwise comparison matrix
4. Allow key informants to pairwise rate decision criteria

The ratio scale for pairwise comparison contains absolute numbers from 1 (equal importance) to 9 (extreme importance) and can be extracted from Saaty (2008). Table 5.5 illustrates an example that compares decision criteria for material selection during concept design, these being durability, cost, weight, surface finish and tolerances.

Table 5.5 Pairwise Comparison Matrix Example for Material Selection during Concept Design

	Durability	Cost	Weight	Surface Finish	Tolerances	Priority
Durability	1	1	2	6	9	***0.362***
Cost	1	1	2	5	8	***0.342***
Weight	½	1/2	1	3	6	***0.192***
Surface Finish	1/6	1/5	1/3	1	2	0.067
Tolerances	1/9	1/8	1/6	1/2	1	0.037

The comparison matrix indicates that durability is rated six times more important than surface finish during the early stage of concept design when selecting materials.

Consequently, the reciprocal value when comparing surface finish and durability equals 1/6, or in other words surface finish is six times less important than durability during this stage. The priorities as shown in Table 5.5 indicate that from the five identified decision criteria, durability (0.362), cost (0.342) and weight (0.192) imply the highest priority when selecting materials during concept design. Hence, trade-off curves must visually display the relation between such important decision criteria with the highest priority. This on the other hand, requires the capturing of such trade-off knowledge and will be explained in Section 5.5.2.3.

5.5.2 Knowledge Capture: Stages 2 and 7 of the LeanKLC

Derived from the three dimensions of knowledge management in product development baseline model, as explained in Section 5.2, this research concludes two different stages of knowledge capturing, namely previous knowledge capturing in stage 2 and dynamic knowledge capturing in stage 7 of the LeanKLC. As shown in Figure 5.9, a previous knowledge capturing comprises the capturing of knowledge from previous projects in (Z) dimension. Dynamic knowledge capturing on the other hand comprises capturing of knowledge which is created during the actual development of a product in vertical (Y) and horizontal (X) dimensions.

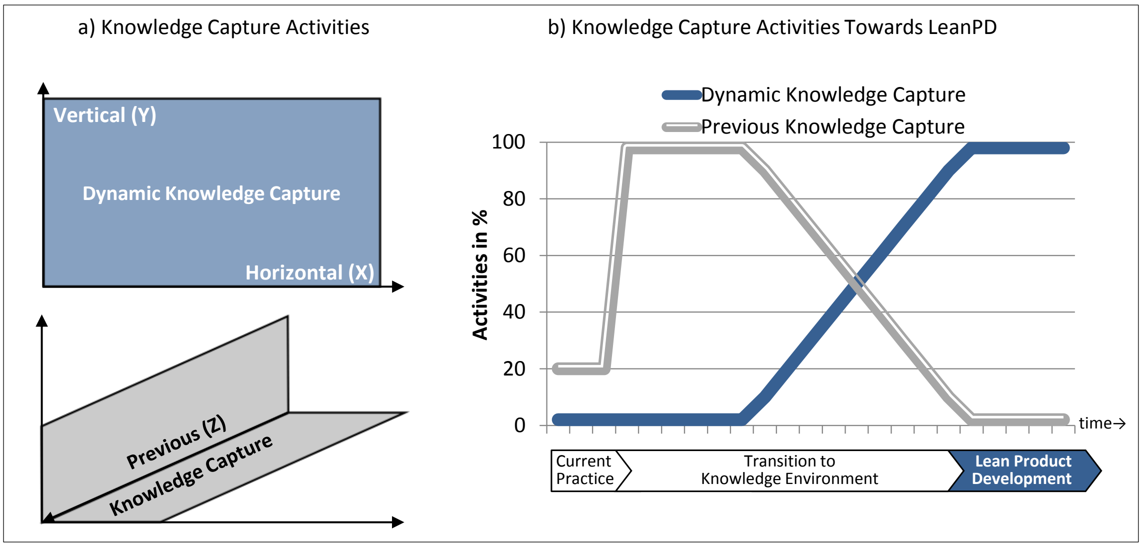


Figure 5.9 Knowledge Capture Types and Activities towards Lean Product Development

Knowledge capturing activities start with previous knowledge capture; hence available knowledge is located as a result from previous LeanKLC stage of identification. After an adequate amount of previous knowledge is captured, the transition into a knowledge environment begins. As shown in Figure 5.9-b, while previous knowledge capture declines over time, the focus during lean product development diverts to dynamic knowledge capture in order to maintain its required knowledge environment. Table 5.6 illustrates the tasks and techniques for the two stages of knowledge capture. Previous knowledge capture comprises the structuring and capturing of the identified knowledge in tasks 2.1 and 2.2, as well as capturing trade-off knowledge in task 2.3.

Table 5.6 Knowledge Capture: Key Tasks and Techniques

Lean Knowledge Life Cycle Stages	Tasks └─Techniques (if applicable)	Tasks supporting LeanKLC stream	
		A3LAMDA	Trade-off Curves
1. Knowledge Identification			
2. Previous Knowledge Capture	2.1 Structure identified Knowledge 2.1.1 Product Data Management		
	2.2 Capture identified Previous Knowledge		
	2.3 Capture Trade-Off Knowledge 2.3.1 Trade-Off Curves		X
3. Knowledge Representation			
4. Knowledge Sharing			
5. Knowledge Integration			
6. Knowledge Use and Provision			
7. Dynamic Knowledge Capture	7.1 Explore ways of Dynamic Knowledge Capture for the LeanPD Knowledge Environment		
	7.2 Dynamically Capture Knowledge during Problem Solving 7.2.1 A3LAMDA Template and Report	X	

Dynamic knowledge capture in stage 7 comprises exploring ways of dynamic knowledge capture for the LeanPD knowledge environment in task 7.1 and to dynamically capture knowledge during problem solving using the A3LAMDA template in task 7.2.

5.5.2.1 Structure Identified Knowledge

Section 4.4.1.1, entitled knowledge capture challenges, provided evidence that product designers and engineers encounter a challenge in structuring product development knowledge. In order to facilitate that knowledge capture supports the principle of a centralised LeanPD knowledge environment (Section 3.3.2), the structuring of identified knowledge is suggested to be aligned with PDM / PLM. However, the industrial field study indicated (Figure 4.6, Section 4.3) that only two out of eleven companies achieved storing large quantity of product development information in a PDM / PLM system. Although a thorough consideration of such technology is out of the scope of this research, the author would like to put forward two potential scenarios to structure the identified knowledge based on the current adaption of product data management systems. These are:

1) Structure the identified knowledge based on the current PDM / PLM system if most product development information is stored and engineers retrieve information regularly from the PDM / PLM system.
2) Guide the structuring of the PDM /PLM system to facilitate dynamic knowledge capturing as well as knowledge use and provision in the envisioned knowledge environment.

5.5.2.2 Capture Identified Previous Knowledge

Section 4.3 (Figure 4.3) highlighted the importance of particular sources of knowledge, including tacit knowledge, previous projects, design standards and rules. However, the existence of different knowledge sources in product development triggers implications for the knowledge capturing task, meaning that there is no universal way to capture knowledge from all the available sources. Capturing of tacit knowledge encounters a particular challenge from an industrial (Section 4.4.1.1) as well as knowledge management research (Nonaka and Konno, 1998) perspective. Therefore directions regarding capturing previous knowledge are suggested based on the identified sources of knowledge and shown in Table 5.7.

Table 5.7 Previous Knowledge Capture based on identified Knowledge Sources

Identified Sources of Knowledge	Characteristic of Knowledge Sources	Suggestions on Previous Knowledge Capture
Tacit Knowledge	- Knowledge in engineers' heads - Difficult to express or articulate	- Develop skill directory to locate knowledgeable persons (see section 5.5.4.1.2) - If tacit knowledge predominate formulate Recommendations
Previous Projects	- Knowledge stored in various documents captured from product development projects	- Adapt LeanPD techniques (Table 5.2) to enhance current project documentation
Design Rules	- Knowledge available to solve domain specific design problems	- Formulate explicit rules - Use If - Then Statements
Design Standards	- Knowledge entails compliance requirements for product and process development	- Formulate explicit constraints - Use If - Then Statement

To address the challenge of capturing tacit knowledge the development of skill directories is an option to locate knowledgeable persons from which tacit knowledge can be acquired through human interaction. However, in case tacit knowledge sources predominate, the formulation of recommendation is suggested, hence providing increased flexibility to capture broad descriptions of encountered experiences.

Previous projects as a source of knowledge are stored in various documents captured from product development projects. The suggestion of capturing knowledge from previous projects is directed to adapt LeanPD techniques that incorporate document templates to enhance current project documentation more suitable to the lean environment. The entire spectrum of tools and techniques discussed in the LeanPD knowledge environment is presented in Table 5.2. This could be achieved using documentation templates such as lessons learned log, benchmark reports, competitor tear down analysis sheets and design notebooks.

It is suggested that previous knowledge capture from located design rules and standards be accomplished by formulating If - Then statements. This was observed as efficient during one industrial application of the LeanKLC (Section 6.3.2), providing the encountered condition behind the captured rules and constraints. On the other hand, design rules and constraints are bound to certain domain experts and so encompass limited capability for re-use among multifunctional product development teams. For this reason (among others), the use of visually supportive techniques such as trade-off curves is employed and explained in following section.

5.5.2.3 Capture Trade-Off Knowledge

The task of capturing knowledge in the form of trade-off curves is related to the decision criteria for particular LeanKLC applications, as discussed in Section 5.5.1.5. Consequently, capturing the relations between such criteria in the form of trade-off curves is vital in order to visually provide product development engineers proven knowledge to support decision making in particular during narrowing the proposed design solutions in the LeanPD environment. Hence, depicting the appropriate type of trade-off curve is equally important. Three different types of trade-off curves are proposed by the author, namely basic plotting of relations, plotting of previous projects knowledge and plotting of previous projects knowledge against a comparative value. Figure 5.10 illustrates knowledge capturing in the form of trade-off curves, based on the decision criteria as explained in Section 5.5.1.5.

Basic plotting of relations comprises the fundamental physics a product development engineer needs in his day to day work. The main aspect of creating this type of trade-off curve is finding essential knowledge which is usually stored in different places in order to speed up the decision making process. In view of that, Example 2 in Figure 5.10 illustrates the impact of weight on cost decision criteria for currently used materials. For plotting previous projects knowledge in the form of trade-off curves, the company has to refer to proven knowledge obtained in previous design solutions. As shown in example 3, Figure 5.10, previous design solutions are plotted against crash performance and weight. A further example 1 in Figure 5.10, illustrates the plotting of process capabilities in which information is obtained as a result of previous manufacturing projects.

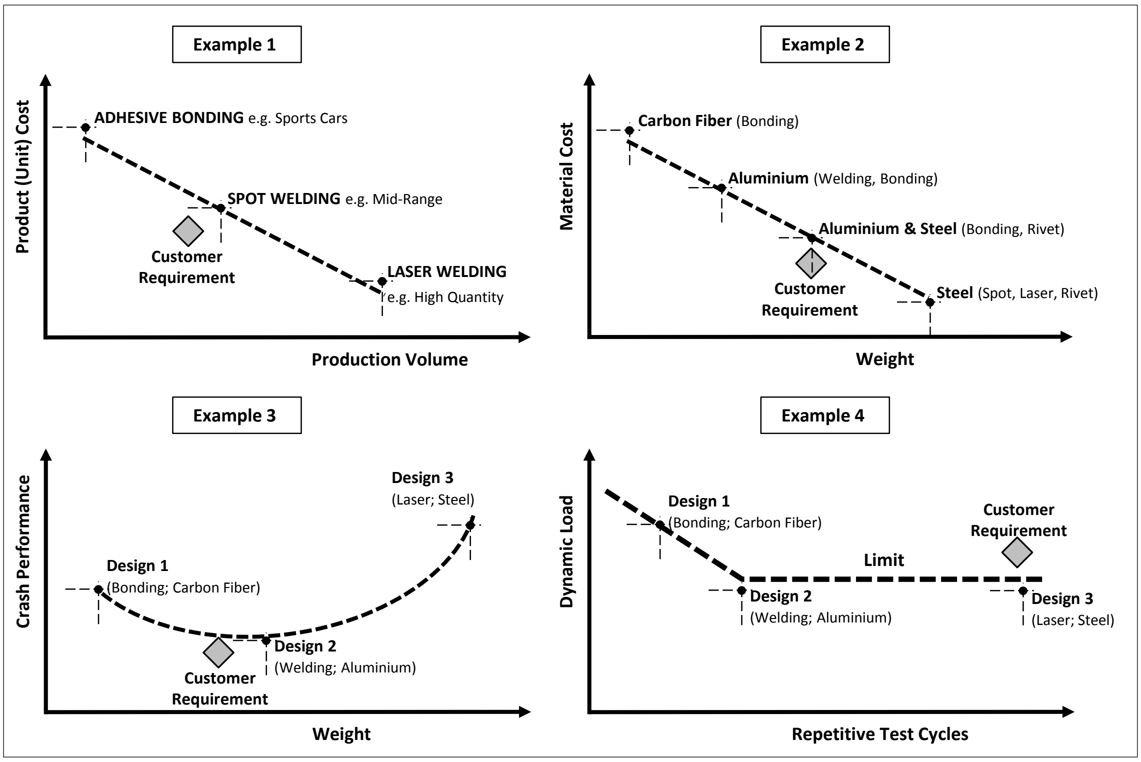


Figure 5.10 Trade-Off Knowledge Capture Examples during Conceptual Design of Car Seat Structures (Maksimovic et al., 2012) based on Mock-Data to illustrate the Concept

In order to maximize the performance of product designs, the third type of trade-off curve considers the plotting of previous projects data against the limit of a chosen performance criteria, such as dynamic load against the respective test cycle of the product design to break, as shown in example 4, Figure 5.10. Such kind of curve intends to illustrate the performance limit for a component, assembly or entire product in order to equip product development engineers with the knowledge related to the highest possible performance capabilities.

Once the type of trade-off curves are determined, capturing of new knowledge is vital in order to ensure that product development engineers use the trade-off curves and integrate them in the decision making process. Figure 5.10 shows that trade-off knowledge capture is obtained from different business functions. A trade-off curve, as illustrated in Figure 5.10, example 1, requires the capturing of relevant information from several different functions. For example, information about product unit cost needs to be obtained from purchasing and finance, whereby production volume information is best found from the production planner or personal working on the manufacturing shop floor. Therefore it is essential to consider two aspects. Firstly, a mechanism that captures up to date knowledge created in a dynamic manner and secondly, to provide adequate templates and user interfaces in order to facilitate knowledge capturing in a multidisciplinary work environment. These particular aspects, being outside the scope of this research, have not been covered and therefore provide direction for future work. On the other hand, the author focused on the dynamic knowledge capturing during problem solving, which is explained in Section 5.5.2.5.

5.5.2.4 Explore ways of Dynamic Knowledge Capture for the LeanPD Knowledge Environment

As illustrated in Figure 5.9 the transition towards a LeanPD knowledge environment requires the realisation of dynamic knowledge capturing. The author believes that dynamic knowledge capturing is a key task to continuously sustain a knowledge environment in LeanPD. However, dynamic knowledge capturing is a new concept and requires the frontloading of needs addressed to its main participants, namely product designers and engineers. Therefore, principles necessary to realising dynamic knowledge capturing for the LeanKLC are defined as following:

a) Establish a method were engineers are motivated[5] to participate
b) Integrate[6] knowledge capturing in product development process
c) Facilitate a process[7] that captures knowledge whilst created
d) Minimise documentation[8] effort

Sources of Evidence
[5] Challenge to motivate engineers to participate in knowledge capture task, section 4.4.1.1.
[6] Challenges to integrate knowledge in the PDP, section 4.4.2.2.
[7] Challenge that knowledge is captured at the end of project, section 4.4.1.1.
[8] Engineers perceive knowledge capturing task as time consuming, section 4.3 (Figure 4.8)

e) Enhance current techniques of the LeanPD knowledge environment to accomplish this task

Given the above, dynamic knowledge capture is accomplished during the actual product design and development activities, such as simulation, prototyping and testing. Accordingly, the next section describes an example of a novel approach developed during this research to dynamically capture knowledge using an A3LAMDA template as an integrated technique in the LeanPD knowledge environment.

5.5.2.5 Dynamically Capture Knowledge during Problem Solving using A3LAMDA Template

Dynamic knowledge capture is accomplished with the enhancement of element number 9 (so what) in the A3LAMDA template, as illustrated in Figure 5.5. This aims to provide designers and engineers a process and technique to capture knowledge whilst solving design problems on products under development. The enhanced element number 9 (so what) of the A3LAMDA template is illustrated in Figure 5.11 and explained as follows.

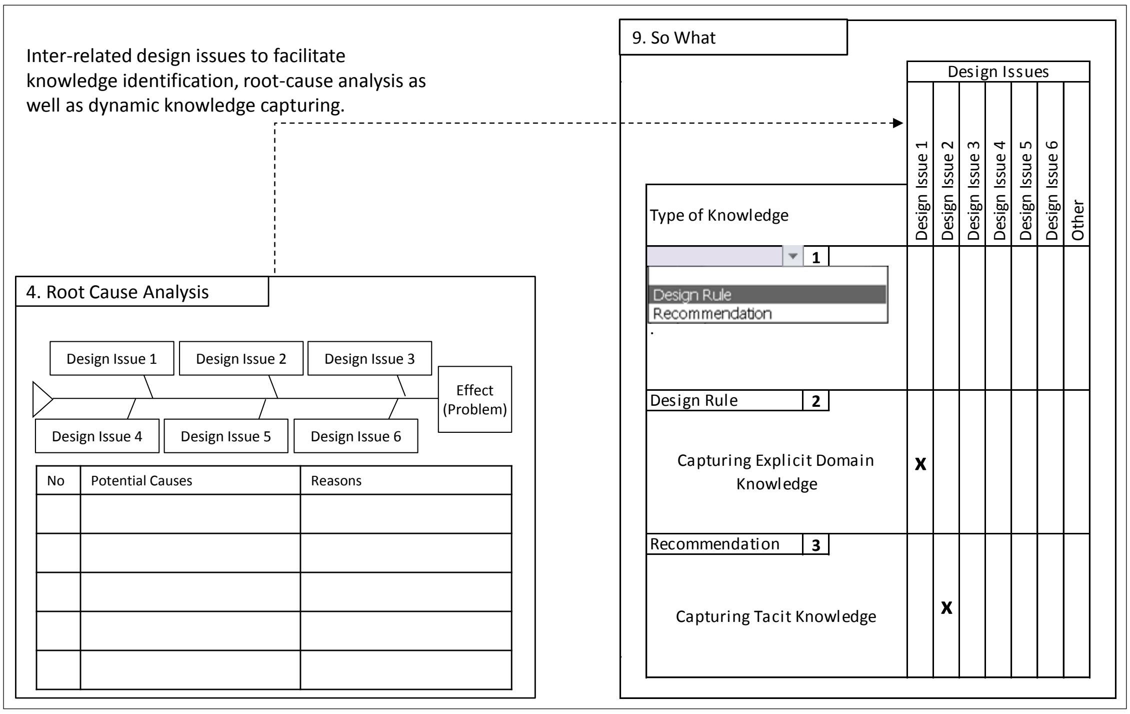


Figure 5.11 Dynamic Knowledge Capturing in A3LAMDA Template

The dynamic knowledge capture element consists of three entry cells per problem solving report, an amount concluded as adequate during the action research. Once knowledge is created the engineers will capture it either as a design rule or a recommendation. The design rule / recommendation will relate to specific design issues which have been previously listed as part of the root cause analysis. Consequently, as shown in Figure 5.11, any knowledge captured in the A3LAMDA report relates to a design issue, meaning that in future engineers can pull related knowledge and accelerate root cause analysis.

5.5.3 Knowledge Representation: Stage 3 of the LeanKLC

Although formal representation of knowledge was not addressed by the lean product development community it is regarded as important to enrich the comprehension of captured knowledge as well as facilitating its computational use.

Table 5.8 Knowledge Representation: Key Tasks and Techniques

Lean Knowledge Life Cycle Stages	Tasks └─Techniques (if applicable)	Tasks supporting LeanKLC stream	
		A3LAMDA	Trade-off Curves
1. Knowledge Identification			
2. Previous Knowledge Capture			
3. Knowledge Representation	3.1 Define Key Knowledge Attributes	X	
	3.2 Graphically Represent Knowledge Provision 3.2.1 Vector Representation of Knowledge Provision	X	
	3.3 Formally Represent Captured Knowledge 3.3.1 Formal Knowledge Representation Techniques		X
4. Knowledge Sharing			
5. Knowledge Integration			
6. Knowledge Use and Provision			
7. Dynamic Knowledge Capture			

The stage of knowledge representation comprises traditional formal knowledge representation techniques in task 3.3 as well as a novel approach for graphical representation of knowledge provision using vectors in task 3.2. However, as illustrated in Table 5.8, the first task 3.1 of knowledge representation is the definition of key knowledge attributes and explained as follows.

5.5.3.1 Define Key Knowledge Attributes

The definition of knowledge attributes is important to enrich meaning as well as the processing of captured knowledge. Knowledge attributes symbolise variables that are investigated during knowledge management initiatives (Holsapple, 2003). However, the spectrum of applicable knowledge attributes in product development is extensive;

these could be tacit versus explicit knowledge (Nonaka, 1991), descriptive versus procedural knowledge (Bonczek et al., 1981) or public versus private knowledge (Holsapple and Whinston, 1996; Holsapple, 2003) to mention just a few.

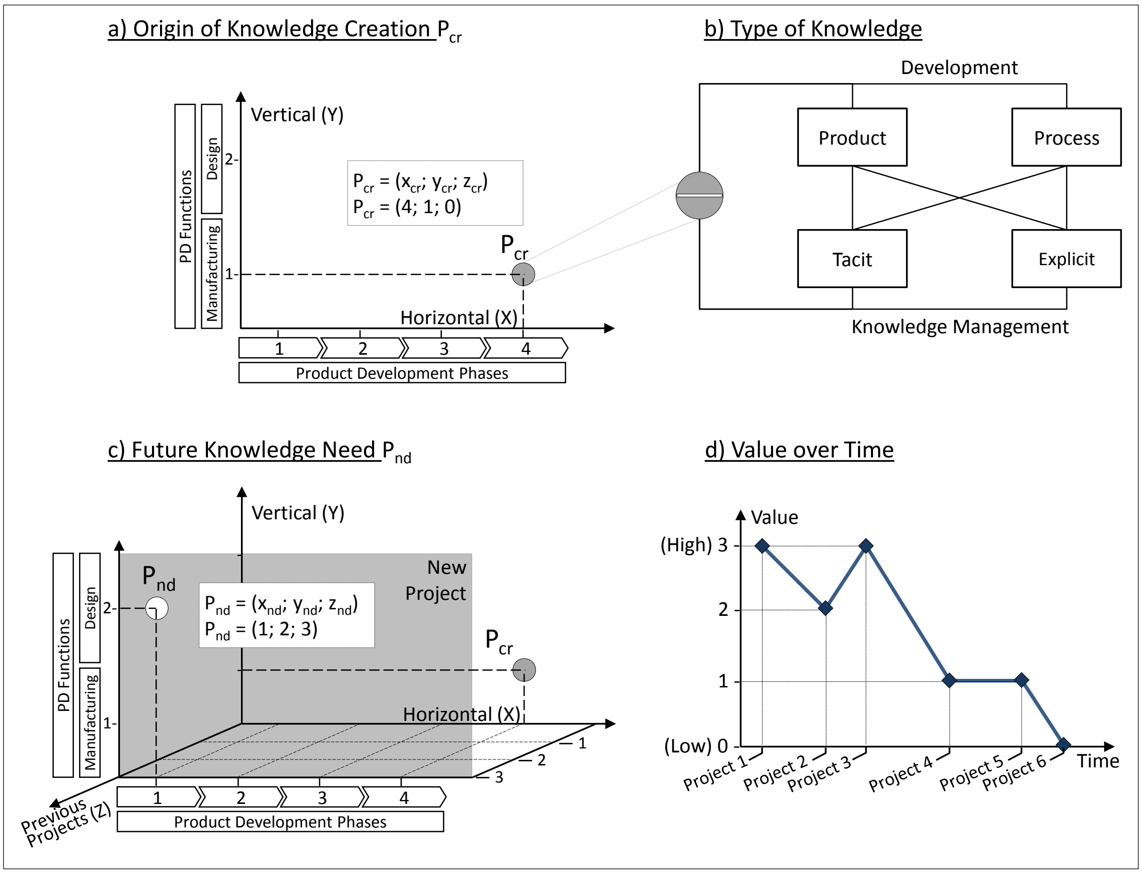


Figure 5.12 Four Key Knowledge Attributes

For these reasons, four key attributes are suggested as being of particular importance to support the LeanKLC as developed in this research and illustrated in Figure 5.12. These are: a) origin of knowledge creation, b) type of knowledge, c) future knowledge need and d) value over time as explained in the following subsections.

5.5.3.1.1 Origin of Knowledge Creation (P_{cr})

The attribute 'origin of knowledge creation' determines the location where the knowledge was initially created as the point P_{cr} within the three dimensions of knowledge management in product development, as illustrated in Figure 5.12-a. This attribute is important to consider for every knowledge captured in order to determine where certain knowledge is available and hence provides an important element for knowledge sharing, a subsequent stage of the LeanKLC. The Cartesian coordinates

(X,Y,Z) of the three dimensions of knowledge management in product development enable the attribute P_{cr} to receive its unique coordinates, these being $P_{cr} = (x_{cr}; y_{cr}; z_{cr})$. Figure 5.12-a shows an example of knowledge created in product development phase number 4 and function number 1 (manufacturing) during project number 0 (first ever project). Consequently, for this example the origin of knowledge creation attribute results in $P_{cr} = (4; 1; 0)$.

5.5.3.1.2 Type of Knowledge

Although product development is an ever repeating problem solving activity, its created knowledge applies to the improvement of either product or process related issues. Consequently, it is possible to distinguish knowledge that is related to the physical product, such as feature based knowledge, but also to the knowledge that is required to process the envisioned product, for example through manufacturing operations. In knowledge management on the other hand, knowledge is largely manifested as tacit or explicit. As a result and in the context of this research, the author depicts two elements that determine the specific type of knowledge, as illustrated in Figure 5.12-b. First, knowledge is either product or process related and second, knowledge is either explicit or tacit. In total, four different types of knowledge are apparent, namely tacit product knowledge, explicit product knowledge, tacit process knowledge and explicit process knowledge.

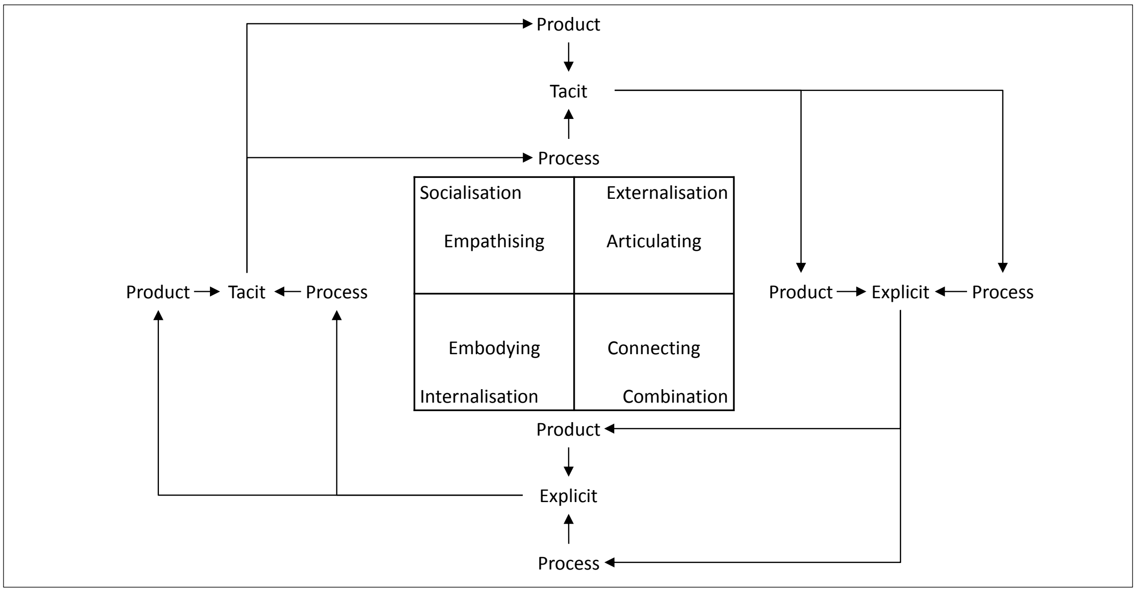


Figure 5.13 Nonaka et al. (2000) Model of Knowledge Conversion during Product and Process Development

Tacit product knowledge comprises the knowledge a designer uses intuitively during the design based on proven experience with limited ability for formal explanation. Explicit product knowledge comprises the knowledge using specific rules and constraints which always apply under given criteria. Tacit process knowledge includes experienced phenomena that allow the operator to process the product in an efficient way. Whereby explicit process knowledge comprises the usage of repetitive process variables for given situations. Given the above, Nonaka's (1991) widely acknowledged model of knowledge conversion allows an enhanced understanding of the four conversion modes during product and process development, as illustrated in Figure 5.13. For example, externalisation occurs during concept development when articulating tacit product knowledge in the form of a customer need into explicit process knowledge in order to realise its manufacturability.

5.5.3.1.3 Future Knowledge Need (P_{nd})

The attribute of future knowledge need P_{nd} as illustrated in Figure 5.12-c is declared in order to provide knowledge within the whole spectrum of three dimensions of knowledge management in product development. This means that knowledge is not only captured and stored, as undertaken in the previous stages of the LeanKLC, but also its trigger points in the product development process are declared for future re-use. Hence, it is expected that only the needed amount of knowledge is provided at the right time and place in order to tackle its associated challenge of knowledge provision, as described in Section 4.4.1. The example in Figure 5.12-c illustrates the attribute of future need being $P_{nd} = (1; 2; 3)$. This means that the knowledge created in P_{cr} is needed in product development phase number 1 and function number 2 (design) during new project number 3. However, in case that same knowledge is needed in several locations, the attribute of future receives multiple variables, such as P_{nd1} and P_{nd2}, all originating from knowledge created P_{cr}.

5.5.3.1.4 Value over Time

Whilst interacting with industrial partners during this research it became evident that the knowledge environment in product development is dynamic. New products and technology constantly evolve alongside their created knowledge. This also means that the value of the knowledge created evolves over time. Consequently, the attribute of value over time, as illustrated in Figure 5.12-d, is vital to monitor its evolution in order to integrate knowledge accordingly in the product development process, which is explained in detail within the associated stage of knowledge integration in Section 5.5.5.4.

5.5.3.2 Graphically Represent Knowledge Provision

In Section 5.2 the baseline model was explained as the three dimensions of knowledge management in product development using Cartesian coordinates. Providing the right knowledge is vital, as engineers expressed during the industrial field study, (Section 4.3), that 79% of design problems could have been solved if the right knowledge had been provided. Hence it is apparent that knowledge is needed at a particular phase and function in the product development process, which was explained as attribute P_{nd} in Section 5.5.3.1.3.

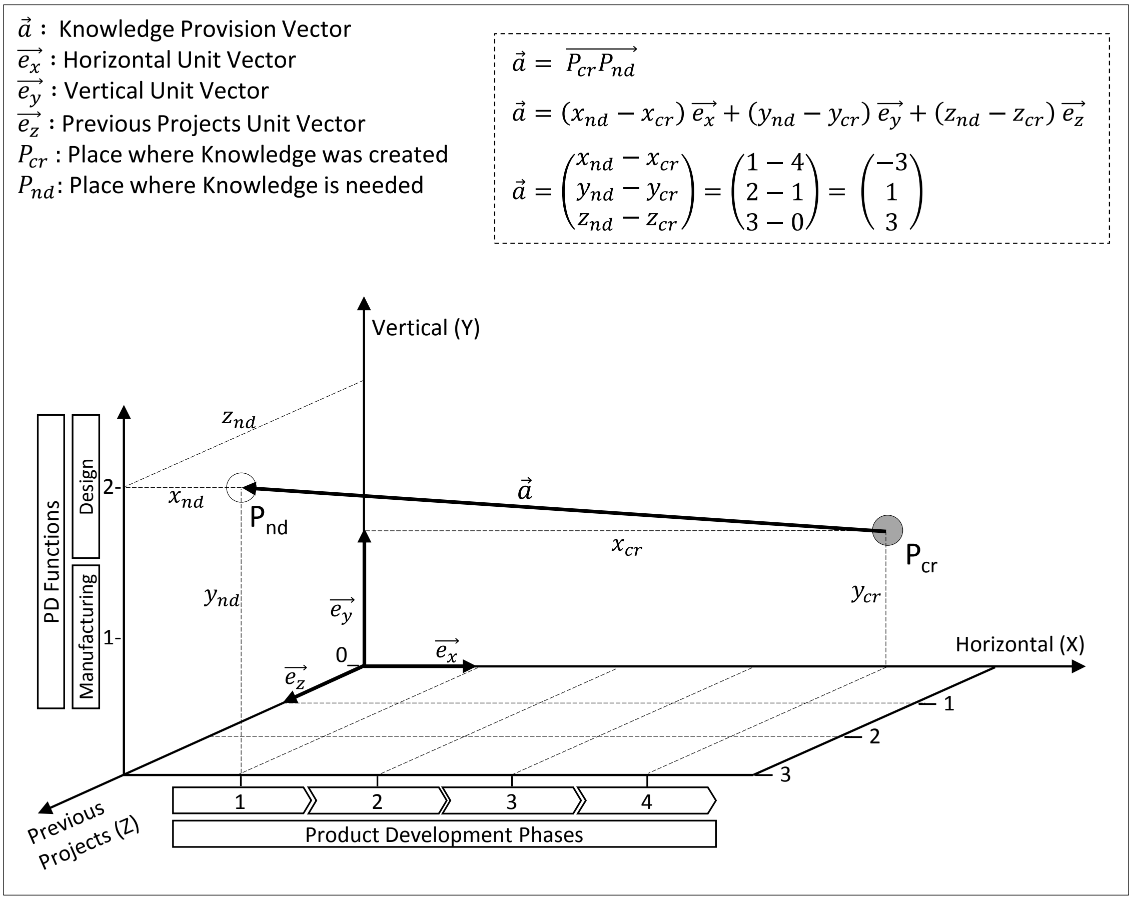


Figure 5.14 Vector Representation of Knowledge Provision

Another attribute, entitled origin of knowledge creation P_{cr}, clarified that such needed knowledge was once created in a certain activity during previous product development. In combination with Cartesian coordinates through the baseline model both attributes, P_{cr} and P_{nd}, receive their unique values within the horizontal (X), vertical (Y) and previous projects (Z) dimensions for a particular knowledge created. Given that, the above knowledge provision is declared as a vector $\vec{a}$ between the two points $\overrightarrow{P_{cr}P_{nd}}$, as illustrated in Figure 5.14.

In order for companies to practice such vector representation of knowledge provision, it is necessary to declare the three unit vectors, namely $\overrightarrow{e_x}$, $\overrightarrow{e_y}$ and $\overrightarrow{e_z}$, according to the actual product development process and if possible in conjunction with set based concurrent engineering. In this chapter, the mathematical definitions for vector representation were adapted from Papula (2011). As shown in Figure 5.14, the horizontal unit vector $\overrightarrow{e_x}$ involves the segmentation of phases in the horizontal direction required to develop a product. The vertical unit vector $\overrightarrow{e_y}$ represents the different functions in the product development process. During set based concurrent engineering on the other hand, $\overrightarrow{e_y}$ represents the set of alternative design solutions. The previous project unit vector $\overrightarrow{e_z}$ entails any product development project undertaken to date. Once unit vectors are declared, the representation of a knowledge provision vector $\vec{a}$ results in:

$$\vec{a} = (x_{nd} - x_{cr})\,\overrightarrow{e_x} + (y_{nd} - y_{cr})\,\overrightarrow{e_y} + (z_{nd} - z_{cr})\,\overrightarrow{e_z}$$

$$\vec{a} = \begin{pmatrix} x_{nd} - x_{cr} \\ y_{nd} - y_{cr} \\ z_{nd} - z_{cr} \end{pmatrix}$$

Figure 5.14 illustrates an example that determines the knowledge provision vector $\vec{a}$ as follows:

$$\vec{a} = \begin{pmatrix} x_{nd} - x_{cr} \\ y_{nd} - y_{cr} \\ z_{nd} - z_{cr} \end{pmatrix} = \begin{pmatrix} 1-4 \\ 2-1 \\ 3-0 \end{pmatrix} = \begin{pmatrix} -3 \\ 1 \\ 3 \end{pmatrix}$$

The interpretation of knowledge provision vector $\vec{a}$ is that knowledge created in P_{cr} has to be provided:

$$\vec{a} = \begin{pmatrix} -3 \\ 1 \\ 3 \end{pmatrix}$$

- at the ***right time***, this being phase 1 - <u>third</u> incremental <u>preceding</u> phase
- at the ***right place***, this being the design function - <u>one</u> function <u>above</u>
- during new PD, this being <u>third</u> incremental <u>proceeding</u> project

As with any vector application, the knowledge provision vector is characterised by its direction and magnitude. The following subsections describe four different vector patterns as particularly apparent in product development based on direction and magnitude.

5.5.3.2.1 Vector Representation of Previous Projects Knowledge Provision

As illustrated in Figure 5.15, the previous projects vector $\vec{a}$ is only represented in a positive Z direction. Therefore, the magnitude of the vector comprises only components in previous projects (Z) direction, that is $z_{nd} - z_{cr}$. The representation in negative Z direction on the other hand is not possible, hence this would mean that knowledge provision occurs back in time, a practically impossible condition.

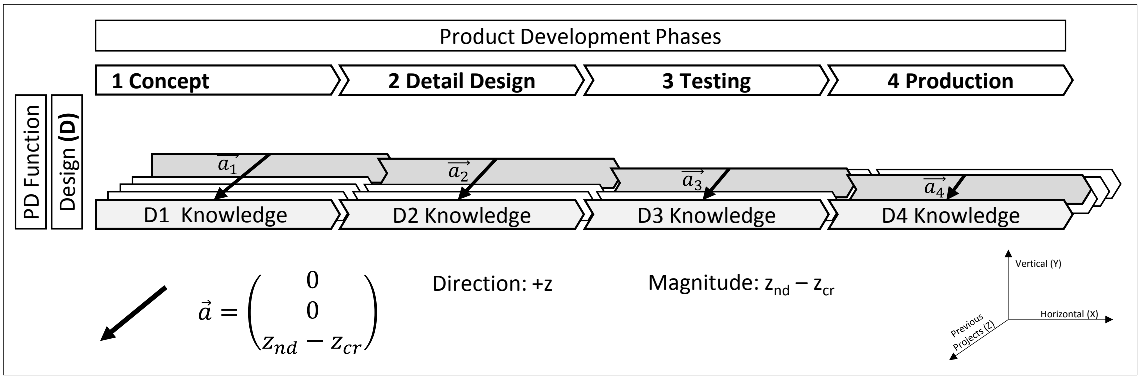


Figure 5.15 Vector Representation of Previous Projects Knowledge Provision

This form of knowledge provision outlines that such particular knowledge is required in the same phase and function as it was originally created. The maximum magnitude is relative to the first ever project or in other words the oldest knowledge available provided to the current product development, illustrated with $\overrightarrow{a_1}$ in Figure 5.15.

5.5.3.2.2 Vector Representation of Horizontal Knowledge Provision

The vector representation of horizontal knowledge provision occurs in positive or negative horizontal direction (X). Its magnitude is determined by the horizontal (X) components $x_{nd} - x_{cr}$, as shown in Figure 5.16.

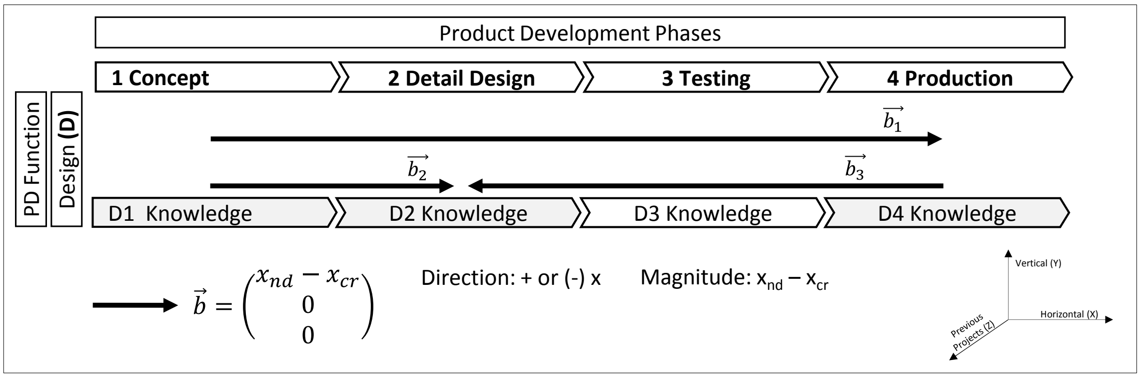


Figure 5.16 Vector Representation of Horizontal Knowledge Provision

Horizontal knowledge provision as illustrated with vector $\vec{b}$, takes place in one particular product development function of which knowledge is needed in another phase. Vector $\overrightarrow{b_1}$ for example, outlines a vector with maximum magnitude, in which knowledge created in the first phase of product development is needed in the last phase within the same project. Vector $\overrightarrow{b_2}$ on the other hand represents a vector with the lowest magnitude in which knowledge is needed in the proceeding phase, equal to unit vector $\overrightarrow{e_x}$. A vector with negative horizontal direction (X) only, characterises knowledge provision caused by design iterations, such as rework, and exemplified as vector $\overrightarrow{b_3}$ in Figure 5.16.

5.5.3.2.3 Vector Representation of Vertical Knowledge Provision

Vertical Knowledge provision vectors, illustrated with $\vec{c}$ in Figure 5.17, are represented in vertical (Y) dimension only and comprise the magnitude $y_{nd} - y_{cr}$. It is possible to represent vertical knowledge provision in positive or negative direction. Vector $\overrightarrow{c_1}$ for example is in positive vertical (Y) direction, meaning that knowledge created in the manufacturing function during the concept phase is provided to the design function within the same phase, as shown in Figure 5.17. Vector $\overrightarrow{c_2}$ on the other hand, represents vertical knowledge provision in another phase and in negative direction, the design function provides knowledge to manufacturing. Vector $\overrightarrow{c_3}$ outlines that the maximum magnitude of vertical knowledge provision depends on the amount of functions adapted in the product development process.

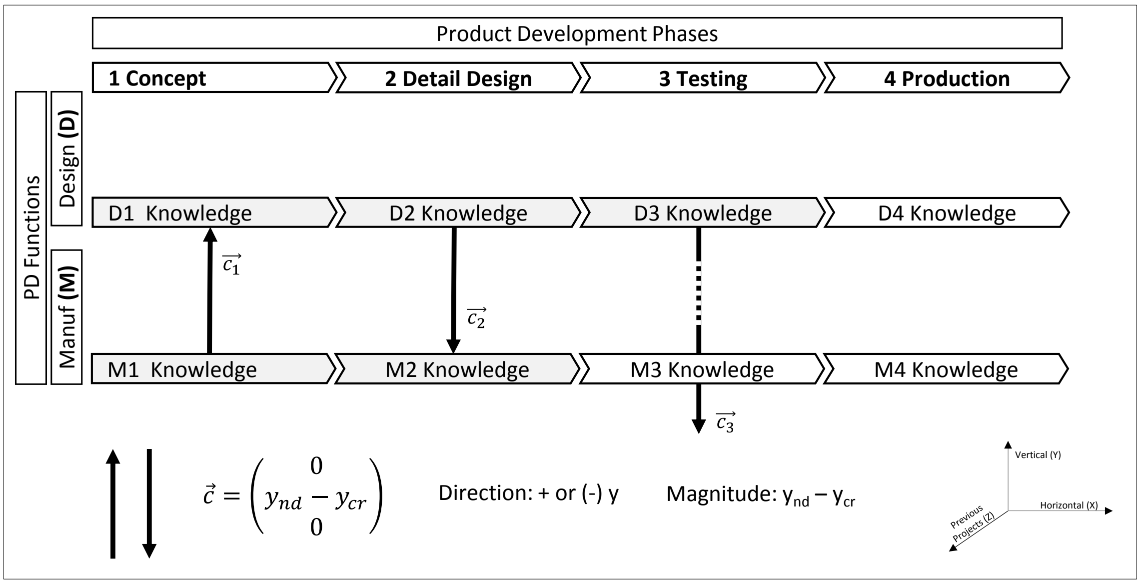


Figure 5.17 Vector Representation of Vertical Knowledge Provision

Vector representation of knowledge provision in vertical (Y) direction becomes another meaning during set narrowing in lean product development in the form of trade off knowledge provision between different sets of design solutions, as illustrated in Figure 5.4. In the same manner, vectors can be used to represent such knowledge provision.

5.5.3.2.4 Vector Representation of Multidimensional Knowledge Provision

Aforementioned vector representations covered isolated the horizontal (X), vertical (Y) and previous projects (Z) dimension. Multidimensional knowledge provision on the other hand comprises the combination of at least two dimensions as illustrated in Figure 5.18. Vector $\vec{d}$ entails components from horizontal (X) and previous projects (Z) dimension. In combination with a positive previous projects (Z) direction, the horizontal (X) component can have positive or negative direction as represented with vectors $\overrightarrow{d_1}$ and $\overrightarrow{d_2}$ in Figure 5.18. This form of knowledge provision is characterised by functions, in this case design, benefiting from their own generated knowledge in various phases of the product development process, though in isolation of other functions.

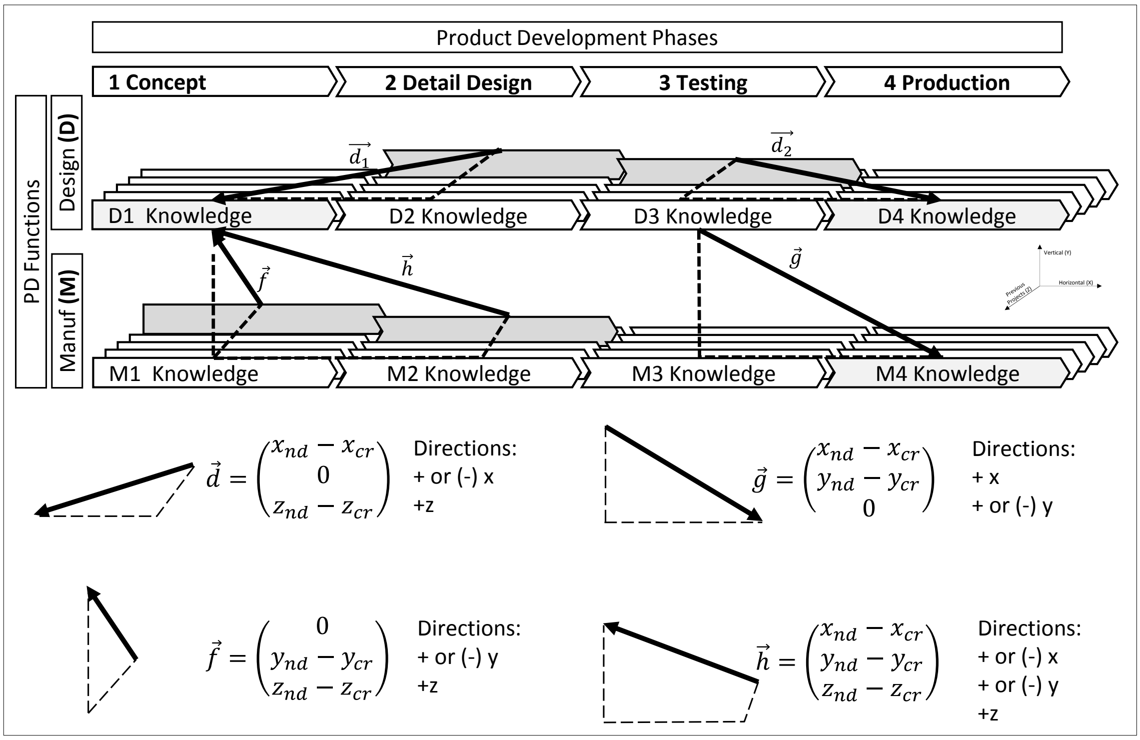


Figure 5.18 Vector Representation of Multidimensional Knowledge Provision

The combination of horizontal (X) and vertical (Y) dimension is represented as vector $\vec{g}$ in Figure 5.18. The directions of $\vec{g}$ comprises negative or positive Y and positive X dimension. Created knowledge is provided to another function, however in a proceeding phase of the product development process. Vector $\vec{f}$ represents knowledge provision in vertical (Y) and previous projects (Z) dimension. The directions include positive Z and positive or negative Y. Knowledge created from previous projects is provided to another function within the same phase, as illustrated in Figure 5.18.

The vector representation of knowledge provision comprising all three dimensions X, Y and Z is exemplified as vector $\vec{h}$ in Figure 5.18. The possible directions include positive Z and positive or negative X and Y directions. Vector $\vec{h}$ represents the provision of knowledge created in the detail design phase in the manufacturing function during a previous project that is needed in the design function during concept development. Representing this entangled circumstance with a simple vector $\vec{h}$ outlines the capabilities as well as the practical potential of the developed technique.

5.5.3.3 Formally Represent Captured Knowledge

The formal representation of knowledge is another task in this stage of the LeanKLC. In this research the author does not emphasise the enhancement of current knowledge representation techniques such as object oriented or semantic web. The emphasis however, is directed towards the awareness that formal knowledge representation is an option to enhance the usability of the captured knowledge.

The appropriate knowledge representation technique depends on the type of knowledge captured in the first place as well as its anticipated re-use. If explicit domain knowledge predominates the captured knowledge, the use of object oriented knowledge presentation is suggested, hence a corresponding logic among the captured knowledge exists. If on the other hand the captured knowledge results in mainly project related knowledge, such as test reports and log-files, then the use of semantic is more appropriate in order to enhance retrieval capabilities at the re-use side. During this research, the use of decision trees also resulted in an effective form of knowledge representation in order to support the decision making process for alternative joining methods, as will be presented in Section 6.3.3.

Moreover, the research in trade-off curves resulted in a suggestion to structure such data in a way that it can be interrelated and represented using a UML class diagram. The suggested structure is based on dividing each trade off variable as a single entity, as shown in Figure 5.19. This structure will aid the generation of various trade-off curves to support different product development activities.

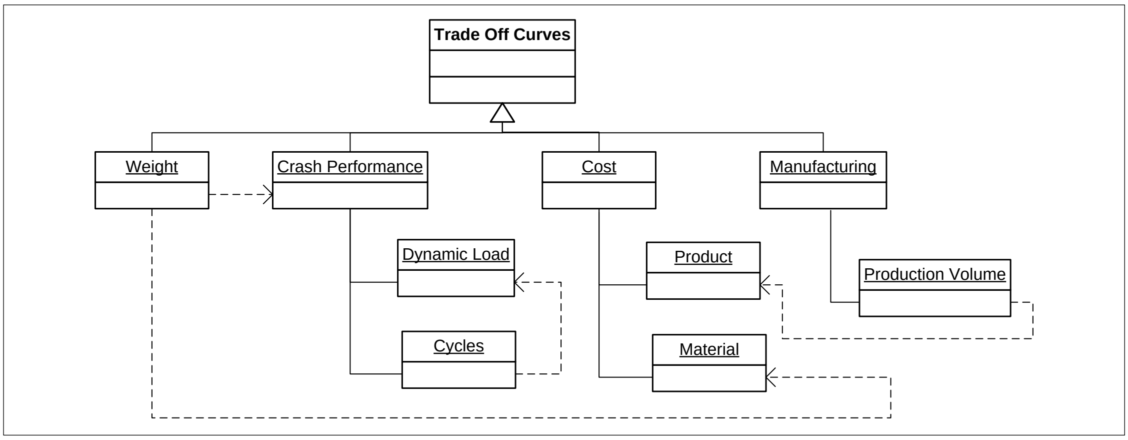


Figure 5.19 Knowledge Representation Structure of Trade-Off Curve Variables (Maksimovic et al., 2012)

It is important to consider upfront the dedication of axes for the different trade-off variables. For example, X-Axis values are generally used for variables such as time, cycles and frequencies. The Y-Axis represents the variable as a function of X, for example for speed, torque and load. The structure of the knowledge model is accomplished according to the decision criteria as defined in stage 1 knowledge identification, Section 5.5.1.5. The detailed knowledge model will illustrate the relations of each trade off variable. The exemplified trade-off curve variables are represented as objects using UML class diagram, as shown in Figure 5.19, where the relation between two objects represents a possible trade off curve. For example, weight is the function of crash performance and illustrated as a dotted arrow.

The author also recommends to restrict focus to the representation of explicit knowledge. Although the knowledge management community discusses a possibility of displaying tacit knowledge using figurative language such as mindscaping, this research is disregarding tacit knowledge from the perspective of knowledge representation due to the technically intensive nature of the product development process. In return, tacit knowledge is given more attention at the knowledge sharing side of the LeanKLC, as explained below.

5.5.4 Knowledge Sharing: Stage 4 of the LeanKLC

As presented in Section 5.4, the stage of knowledge sharing encountered the most potential links to tools and techniques regarding the knowledge environment in the lean product development literature. Hence, knowledge sharing is predominantly shaped by lean product development demanding active interaction of product designers and engineers and hence relies on informal techniques of which potential is realised on a daily basis.

Table 5.9 Knowledge Sharing: Key Tasks and Techniques

Lean Knowledge Life Cycle Stages	Tasks └─Techniques (if applicable)	Tasks supporting LeanKLC stream	
		A3LAMDA	Trade-off Curves
1. Knowledge Identification			
2. Previous Knowledge Capture			
3. Knowledge Representation			
4. Knowledge Sharing	4.1 Centralise Knowledge and Appoint Knowledge Owners 4.1.1 Know-How Database 4.1.2 Skill Directory		
	4.2 Facilitate Knowledge Sharing 4.2.1 Obeya 4.2.2 Continuous Improvement		
	4.3 Share Knowledge through Visualisation 4.3.1 Visual Management	X	X
5. Knowledge Integration			
6. Knowledge Use and Provision			
7. Dynamic Knowledge Capture			

However, making knowledge and those who own it available is fundamental to accomplishing this stage and as such presents the first task 4.1, as illustrated in Table 5.9. The second task 4.2 comprises the facilitation of knowledge sharing as an integrated element in the product development process followed by sharing knowledge through visualisation in task 4.3.

5.5.4.1 Centralise Knowledge and Appoint Knowledge Owners

This task encompasses the storing of knowledge in a centralised database as well as appointing knowledge owners. The former is derived from the lean product development whereas the latter is a technique from knowledge management.

5.5.4.1.1 Know-How Database

The essence of knowledge sharing is to first of all make the knowledge available. Any knowledge needed phase, function or activity (P_{nd}) shall have access to the identified and captured knowledge through a centralised database, preferably using a product data management system. Even though companies struggle to retrieve already captured knowledge of such systems, as outlined in Section 4.4.2, declaring and maintaining the attribute value of time (Section 5.5.3.1.4) in combination with knowledge integration a following stage of the LeanKLC in Section 5.5.5 intends to address this challenge.

5.5.4.1.2 Skill Directory

Theoretically agreed, (Section 3.6), as well as practically proven, (Section 4.3), it is not possible and therefore not advised to try to capture and store the entire corporate knowledge which especially implies to tacit knowledge. Moreover, the extensive usage of product data management systems decreases communication and human interaction among designers and engineers, as reported in Section 4.4.2. For these reasons, knowledge sharing is suggested to have an informal means using a directory of those human experts who have particular knowledge, or in other words to locate each of the knowledge created P_{cr} points. This is achieved through the use of yellow pages, also known as knowledge pointers or skill directories. Yellow pages entail the contact details as well as location (phase, function, activity) of experts that have knowledge in a particular domain, field, product, process, customer or any other instance related to product development.

5.5.4.2 Facilitate Knowledge Sharing

The previous tasks explained ways of knowledge sharing by using a technology and method. This task on the other hand, comprises the facilitating of knowledge sharing using formal techniques integrated into the product development process, including obeya and continuous improvement.

5.5.4.2.1 Obeya

Obeya in the perspective of knowledge sharing is the place, or in translation big room, where multifunctional engineers meet to accelerate communication as well as decision taking. Hence, the establishment of such room facilitates knowledge sharing through intentional settings such as integration and reflection events. This formal way of communication is seen as vital to address its challenge related to knowledge sharing, as presented in Section 4.4.2.

5.5.4.2.2 Continuous Improvement

Continuous improvement is characterised by achieving defined targets, mainly related to problem solving, of which continuous process is supported by PDCA or LAMDA cycle and improvement manifests itself by standardisation. However, continuous improvement requires intense sharing and more importantly release of personal knowledge among designers and engineers, which is a challenge described in Section 4.4.1. The facilitation of such activity is realised through a relational setting which comprises multifunctional teams as well as chief engineers from whose rich experience the team can benefit. Establishing multifunctional teams is essential in order to eliminate over the wall communication as well as to encourage the technique of group problem solving known as nemawashi. Another example to facilitate knowledge sharing is the establishment of a ringi system, a formal decision making process in which designers and engineers are given the freedom to share knowledge related to continuous improvement in a bottom-up approach.

5.5.4.3 Share Knowledge through Visualisation

Sharing knowledge through visualisation focuses purely on the circulation of supporting visual management techniques such as trade-off curves, A3LAMDA templates and reports, visual project boards and health charts. This task of knowledge sharing is entirely paper based in order to establish knowledge sharing beyond computational skill and knowledge format compatibility. In this research the capabilities of using an A3LAMDA template and report for knowledge sharing were explored, which also required the enhancement of certain elements, explained as follows.

Figure 5.20 illustrates how the A3LAMDA report is envisioned to support knowledge sharing. The main aspect of the approach is the visualisation, meaning that during problem solving several printouts of an A3LAMDA report are circulated within their different stages of completion. It is important to circulate the report in places where engineers frequently meet and most importantly in the obeya room. The author suggests three main stages of A3LAMDA report printout circulation.

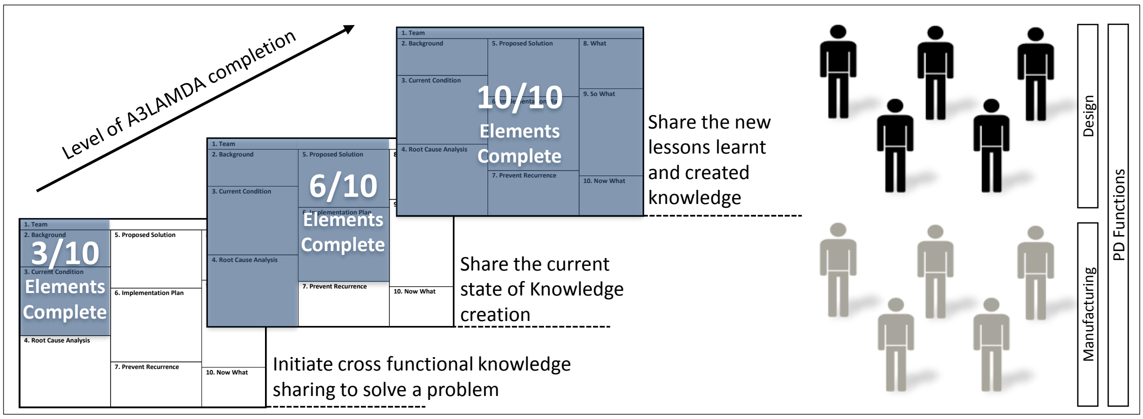


Figure 5.20 Knowledge Sharing through Visualisation

Firstly, during the early stages of problem solving the A3LAMDA report comprises the completion of the first three elements termed team, background and current condition. At this stage a circulation of printouts is vital in order to make engineers aware and invite them to participate in the problem solving activity and share knowledge among a multidisciplinary team. For example, if an engineer solved a similar problem in the past, a printout at this stage will indicate that a similar problem reoccurred, which will give the experienced engineer the possibility to contact the problem solving team and share the knowledge.

Secondly, during root cause analysis, proposed solution and implementation plan, when the A3LAMDA completions comprises six out of ten elements, the printouts of the A3LAMDA report share the results of the created design solutions.

Thirdly, the circulation of fully completed A3LAMDA report printouts is envisioned. Even though the documentation of the report is completed at this stage, the printouts will illustrate the lessons learnt and created knowledge as a result of problem solving and therefore share knowledge to the engineering audience.

Despite the printout circulation, knowledge sharing, as proposed in Section 5.4.1, was formally integrated into the A3LAMDA template by enhancing the ‘proposed solution’ and ‘prevent recurrence’ elements. During industrial collaboration, it was observed that information related to test performances of proposed design solutions are summarized in lengthy documents where knowledge is hard to locate. The enhanced proposed solution element number 5, as illustrated in Figure 5.21 consists of entry cells for number, solution, type of solution and effectiveness. Type of solution covers the assessment if the solution is temporary or permanent. For effectiveness engineers indicate the performance of the design solution to solve the problem, this being not effective, somewhat effective or very effective.

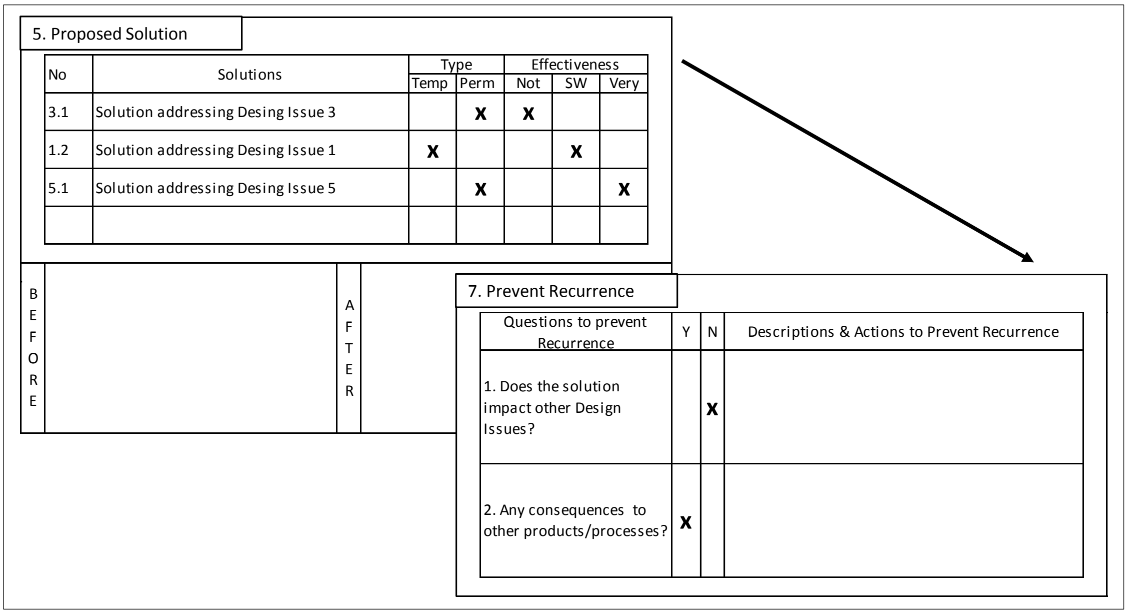


Figure 5.21 Enhanced Proposed Solution and Prevent Recurrence Elements in A3LAMDA Template to encourage Knowledge Sharing

Hence, root cause analysis will result in proposed design solutions; the numbering is taken over from the roots cause analysis as presented in Section 5.5.1.4. As such, engineers can track back how accurately the root-cause analysis was addressed. It also shows that not necessarily all root-causes end up in a proposed design solution, again an indicator of the accuracy as well as the sequence of finding solutions to a design problem.

The capability of this approach in terms of knowledge sharing is the exposure of performance capabilities for different proposed design solution. It shows for example that although design solution 3.1 in Figure 5.21 was a permanent solution; it was not effective to solve the problem. Nevertheless, it is a lesson learnt which will be shared within the problem solving team as well as documented for later re-use. Real knowledge is created and shared when finding a solution to a problem which in best cases leads to a permanent solution that is very effective, as illustrated in Figure 5.21 with design solution 5.1.

The enhancement of the prevent recurrence element number 7 was undertaken by including the table, as illustrated in Figure 5.21 in order to stimulate knowledge sharing among engineers once a design solution is found and verified. The element consists of two questions to prevent recurrence, the resulting answers to the questions being either Yes or No and a description and action to prevent recurrence. The first question investigates consequences for other design issues; hence it is possible that solving one problem increases or creates another. The second question directs the problem solving team to investigate whether there are any consequences for other products or processes.

If either of the questions imply with a YES, the problem solving team communicates the proposed solution to the affected instance as well as shares the resulted knowledge created. This aims to stimulate an informal cross-functional communication method aiming at sharing up to date knowledge, which can be regarded as addressing over the wall communication, a major challenge in product development, as reported in Section 4.4.1.

5.5.5 Knowledge Integration: Stage 5 of the LeanKLC

Stage 5 of the LeanKLC considers knowledge captured as an integrated part of the product development process. During empirical data classification (Section 4.4), it was evident that such integration is largely influenced by two main challenges, namely existing IT-infrastructure as well as the range of decision taking activities.

Table 5.10 Knowledge Integration: Key Tasks

Lean Knowledge Life Cycle Stages	Tasks	Tasks supporting LeanKLC stream	
		A3LAMDA	Trade-off Curves
1. Knowledge Identification			
2. Previous Knowledge Capture			
3. Knowledge Representation			
4. Knowledge Sharing			
5. Knowledge Integration	5.1 Gather Functional Requirements		
	5.2 Adapt a System Architecture	X	
	5.3 Integrate Knowledge in a Centralised Knowledge Base	X	
	5.4 Integrate Knowledge in the Product Development Process	X	
6. Knowledge Use and Provision			
7. Dynamic Knowledge Capture			

Hence, gathering functional requirements in task 5.1 and adapting a system architecture in task 5.2, as illustrated in Table 5.10 intend to guide the integration of captured knowledge in an IT Infrastructure within the context of a knowledge environment for lean product development. The remaining tasks on the other hand, address the integration of captured knowledge to support decision taking activities. These include the integration of knowledge in a centralised knowledge base in task 5.3, as well as in the product development process in task 5.4.

5.5.5.1 Gather Functional Requirements

The gathering of functional requirements intends to familiarise future stakeholders with the envisioned knowledge environment. Moreover, it provides an initial assessment and prioritisation of anticipated key elements before developing a system. The requirements gathering for a knowledge based environment was presented in Section 4.2, from which companies can adopt key elements and most importantly the template and methodology to accomplish this task.

5.5.5.2 Adapt a System Architecture

One of the key aspects of this stage of the LeanKLC comprises the integration of the captured knowledge in a software environment the engineers can use during product design and development. Figure 5.22 illustrates a conceptual system architecture particularly suitable for the developed LeanKLC, which comprises three main layers, namely user, application and knowledge base. The layout of the system architecture was guided by empirical data collection during requirements gathering, as presented in Section 4.2 targeting to logically arrange stages of dynamic knowledge capturing and provision.

The user layer considers the activities related to the product development process. The application layer defines the functional activities of the system and consists of dynamic knowledge capturing, knowledge use and provision, and knowledge maintenance. The knowledge base stores new information and knowledge in a structured way, e.g. from completed A3LAMDA reports, but also collects usefulness ratings of re-used knowledge, as illustrated with a dotted line in Figure 5.22.

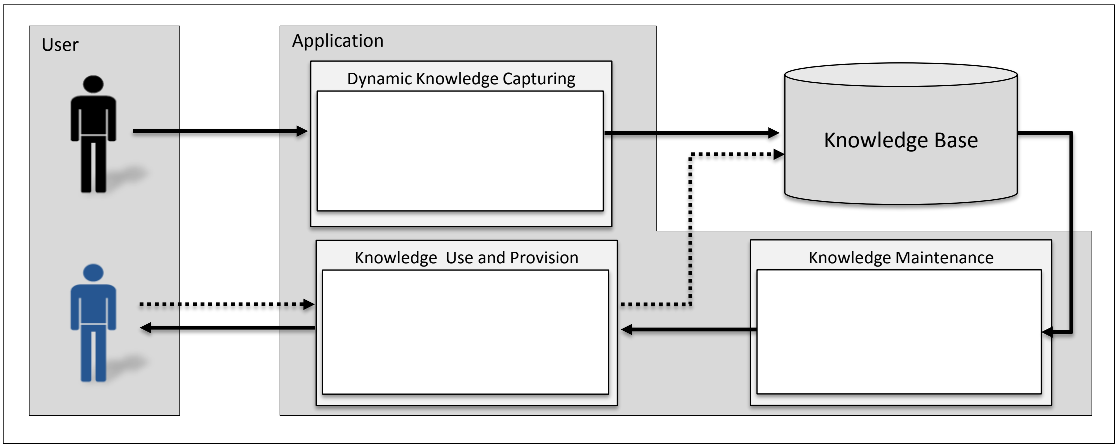


Figure 5.22 Generic Conceptual Knowledge System Architecture to facilitate Dynamic Knowledge Capture as well as Knowledge Use and Provision

As elaborated in this research, the application of knowledge capturing provides a user interface and template for designers and engineers to complete an A3LAMDA report and dynamically capture knowledge as described in Section 5.5.2.5. Knowledge maintenance then evaluates and prioritises the re-used knowledge to adequately integrate it into the product development process. Hence, knowledge use and provision application entails the interface to provide relevant knowledge through e.g. via checklists, knowledge pull or as needed during product development, formerly declared as P_{nd} in Section 5.5.3.2. The following sections described the associated tasks in sequential order to realise knowledge integration related to the knowledge base as part of the system architecture.

5.5.5.3 Integrate Knowledge in a Centralised Knowledge Base

The following presents a possible scenario in order to facilitate that the knowledge captured as a result of solving a problem could be stored in a software form, in order to be available in an accurate way for future projects. The key element of such integrated knowledge base is the A3LMADA report. The detailed industrial application of the work presented in this section is presented in Section 6.2.5, based on the EMC application for the automotive electrical subassembly.

In order to facilitate dynamic knowledge capturing, it is important to interlink elements of the A3LAMDA template with the knowledge base. The intention is to undergo and document problem solving in a knowledge base at the same time as completing an A3LAMDA report. Under this condition, the status of dynamic knowledge is achieved, as knowledge capturing is not conceived as additional activity.

As such, the problem solving team does not manipulate or make entries in the knowledge base; it only works with the provided application of which templates are linked to the knowledge base and enables automated data entry. However, to achieve this status, the knowledge base needs a supportive structure as well as a logic in the amount of data stored, in order not to overcrowd and complicate knowledge retrieval, which is a known industrial challenge, as reported in Section 4.3.

The proposed knowledge base structure is horizontally aligned and comprises sections for failure documentation, problem solving, knowledge capture and maintenance, as illustrated in Figure 5.23. This means that data entry for one problem solving activity is completed horizontally. New entries in the knowledge base on the other hand, populate vertically, as shown in Figure 5.23.

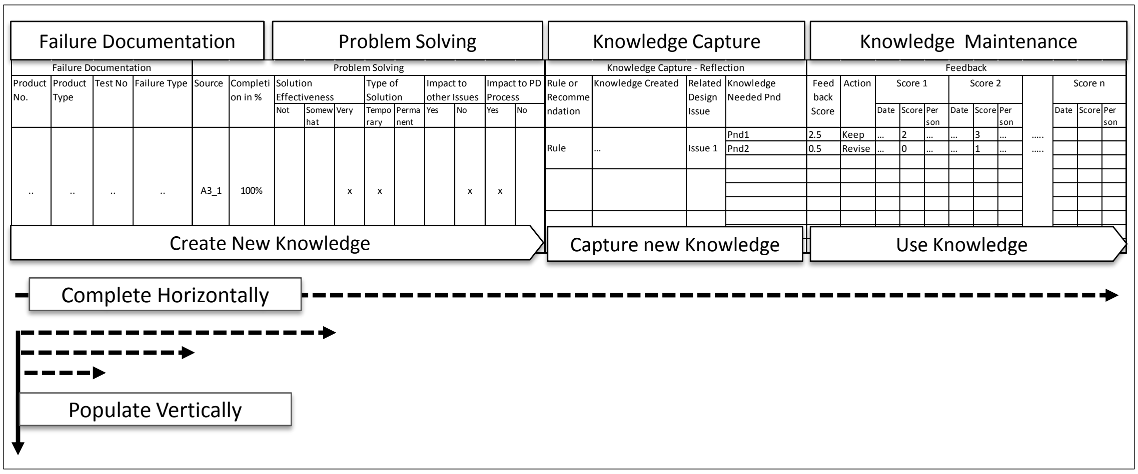


Figure 5.23 Proposed Sections of Knowledge Base Structure to support Knowledge Integration based on A3LAMDA LeanKLC Stream

The proposed sections in the knowledge base structure are aligned to support key stages of the LeanKLC. Knowledge creation occurs when a problem to a particular failure is solved. Another section captures the resulted knowledge of which usage is documented in the knowledge maintenance section. The details of the proposed sections are described as follows.

5.5.5.3.1 Structure the Knowledge Base according to A3LAMDA Problem Solving

The failure documentation section includes the key information about the scope of the problem solving activity. As shown in Figure 5.24, these could include for instance, product number, product type, test number and failure type. The main purpose of this section is traceability, meaning that this information will enable the filter and identification of the associated knowledge in future re-use. In this section, data input is not complicated as all the information is taken directly from the A3LAMDA template. Nevertheless, definition of appropriate data entry for failure documentation is important in the case of considering alternative knowledge capturing methods not explored within the scope of this research.

		Failure Documentation				Problem Solving										
		Product No.	Product Type	Test No	Failure Type	Source	Completed A3LAMDA Elements	Solution Effectiveness			Type of Solution		Impact to other Issues		Impact to PD Process	
No	Date							Not	Somewhat	Very	Temporary	Permanent	Yes	No	Yes	No
1	..	..	..	..	..	A3_1	10			x	x			x	x	

Figure 5.24 A possible Knowledge Base Structure for Failure Documentation Section and Problem Solving

Storing every documented item from the A3LAMDA problem solving report in a knowledge base would result in huge data sets. Therefore the knowledge base elements have been summarized into those that provide information about the overall problem solving performance and include document source, completion, solution effectiveness, type of solution, impact on other issues and impact on other product development processes, as illustrated in Figure 5.24.

The document source provides the path to the related A3LAMDA problem solving report. During the activity of proposed solution, presented in Section 5.5.4.3, it is expected that multiple solutions are generated. However, the information stored in the knowledge base comprises only the implemented design solution, which is the core evidence to assess the problem solving activity as well as product design improvement. The similar applies to the type of solution; it captures only the type of solution that applies to the implemented design solution. Applying such logic is seen as vital in order not to overcrowd the knowledge base and capture only meaningful information in the knowledge base.

5.5.5.3.2 Structure the Knowledge Base to support Knowledge Capture and Maintenance

The knowledge capture section of the knowledge base aims at storing the knowledge as a result of problem solving documented in the A3LAMDA report. As shown in Figure 5.25, the required entries from the A3LAMDA report include: type of knowledge (rule or recommendation), knowledge created, related design issue and knowledge needed P_{nd}.

Knowledge Capture - Reflection				Knowledge Maintenance											
Rule or Recommendation	Knowledge Created	Related Design Issue	Knowledge Needed Pnd	Feed back Score	Action	Score 1			Score 2				Score n		
						Date	Score	Person	Date	Score	Person		Date	Score	Person
Rule	…	Issue 1	Pnd1	2.5	Keep	…	2	…	…	3	…	…..			
			Pnd2	0.5	Revise	…	0	…	…	1	…	…..			

Figure 5.25 A possible Knowledge Base Structure for Knowledge Capture and Maintenance

Hence, the proposed A3LAMDA template entails three entry cells for dynamic knowledge capture (Section 5.5.2.5) and each knowledge captured can have up to three required activities for knowledge needed P_{nd} attribute (Section 5.5.6.3), the total number of rows per problem solving activity equals nine. This means that every knowledge captured and its associated activity of knowledge needed P_{nd} has its individual and unique row in the knowledge base. Accordingly, the knowledge maintenance section is about the end-user evaluating the usefulness of such individual pieces of knowledge stored in the knowledge base.

The proposed structure of the knowledge base makes it possible to evolve horizontally, meaning that knowledge maintenance can collect as many usefulness evaluations as long as the knowledge is re-used without interfering with other entries. Moreover, as shown in Figure 5.25, every knowledge is rated individually within its needed activity P_{nd} in product development, meaning that individual knowledge evolves independently in a particular activity.

For example, if a knowledge provided is rated constantly low in a certain needed activity P_{nd1} it would be suggested to discard it. However, if the same knowledge is rated very high in another activity P_{nd2}, the knowledge base will continue storing feedback data for activity P_{nd2} only. Hence, the knowledge base structure allows knowledge to progress individually in separate functions, phases or activities in the product development process. The following section describes how collected feedback data is integrated in the product development process.

5.5.5.4 Integrate Knowledge in the Product Development Process

As part of the knowledge management, knowledge needs to be maintained and upgraded in order to be correctly integrated in the product development process. Hence this research proposes the following mechanism.

Once knowledge is captured and stored it becomes part of the knowledge base as well as occupying a unique position within the three dimensions of knowledge, as illustrated in Figure 5.26-a. As time progresses knowledge evolves, meaning that its usefulness to support decision taking in product development changes. For example, some of the previously captured knowledge becomes common practice and hence does not require any further form of knowledge provision for experienced designers and engineers. Given the above, knowledge maintenance is accomplished by determining the usefulness of provided knowledge through the knowledge attribute named 'value over time', as presented in Section 5.5.3.1.4.

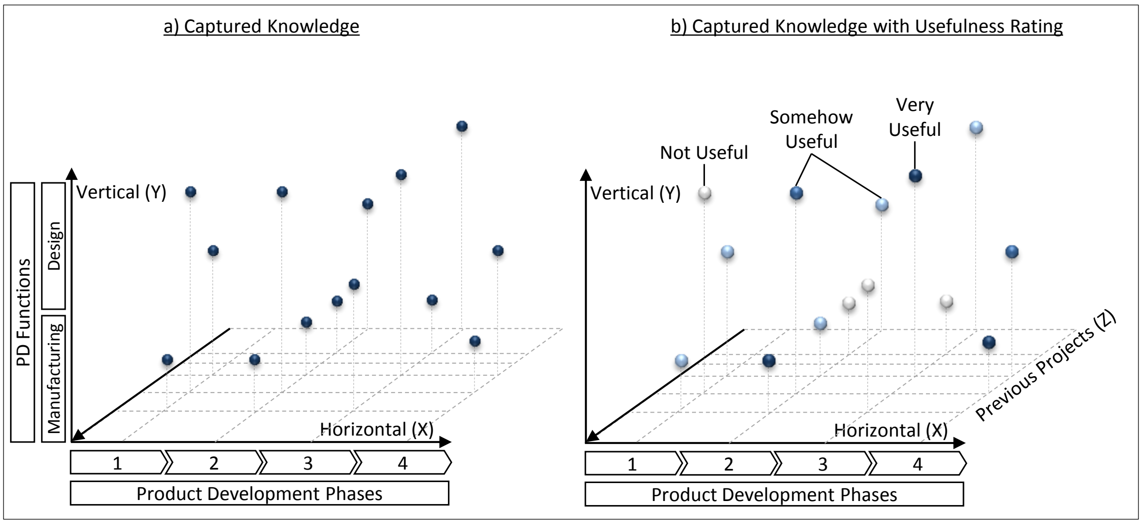


Figure 5.26 Captured Knowledge in Product Development with usefulness Rating after Re-use

As shown in Figure 5.26-b, every knowledge captured conceives a rating of usefulness. However, the only sources capable of providing adequate evaluation are the knowledge users, specifically product designers and engineers. Consequently, the collection of such data is accomplished during knowledge use and provision in a subsequent stage of the LeanKLC, which will be explained in Section 5.5.6.4.

The above knowledge maintenance is based on a Likert scale by evaluating a feedback score for the knowledge provided as a function over time. The Likert scale method is used in order to establish a scoring mechanism that is easy to understand as well as compatible throughout the product development process. Once engineers use the knowledge, an additional activity requires the indication of usefulness of the knowledge, which in this research is demonstrated using a choice of four numerical values.

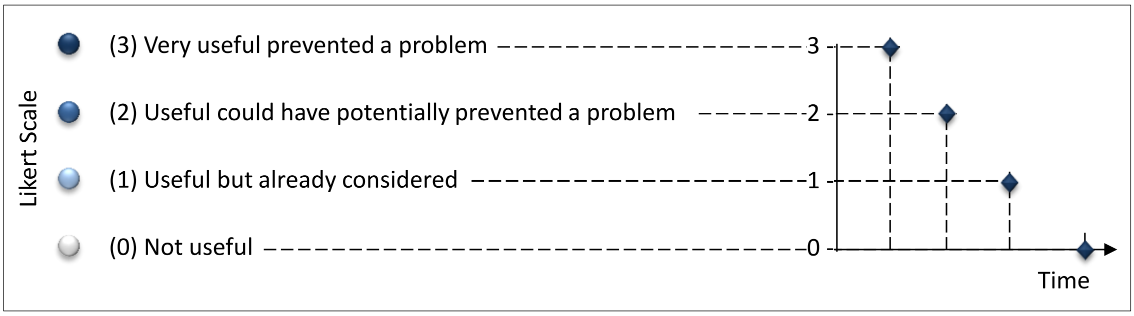


Figure 5.27 Likert Scale for Usefulness Evaluation during Knowledge Use and Provision

As shown in Figure 5.27, the magnitude of usefulness on the Likert scale is defined as not useful (0), useful but already considered (1), useful could have potentially prevented a problem (2) and very useful prevented a problem (3). A detailed method of determining a knowledge re-use value according to different product development scenario patterns of usefulness evaluation is explained in Appendix C.

5.5.6 Knowledge Use and Provision: Stage 6 of the LeanKLC

The stage of knowledge use and provision is illustrated in Table 5.11 and has two facets. Firstly, it addresses the knowledge use side, emphasising the use of trade-off knowledge during the set narrowing phase in task 6.1.

Table 5.11 Knowledge Use and Provision: Key Tasks and Techniques

<table>
<tr><th rowspan="2">Lean Knowledge Life Cycle Stages</th><th rowspan="2">Tasks
└─Techniques (if applicable)</th><th colspan="2">Tasks supporting LeanKLC stream</th></tr>
<tr><th>A3LAMDA</th><th>Trade-off Curves</th></tr>
<tr><td>1. Knowledge Identification</td><td></td><td></td><td></td></tr>
<tr><td>2. Previous Knowledge Capture</td><td></td><td></td><td></td></tr>
<tr><td>3. Knowledge Representation</td><td></td><td></td><td></td></tr>
<tr><td>4. Knowledge Sharing</td><td></td><td></td><td></td></tr>
<tr><td>5. Knowledge Integration</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">6. Knowledge Use and Provision</td><td>6.1 Use Trade-off Knowledge during Set Narrowing Phase
6.2.1 Trade-Off Curves</td><td></td><td>X</td></tr>
<tr><td>6.2 Establish a Mechanism that Supports Knowledge Provision
6.3.1 A3LAMDA Template</td><td>X</td><td></td></tr>
<tr><td>6.3 Provide Useful Knowledge at the Right Time and Place</td><td>X</td><td></td></tr>
<tr><td>7. Dynamic Knowledge Capture</td><td></td><td></td><td></td></tr>
</table>

Secondly, in the context of knowledge provision, this stage provides novel ideas on the largely anticipated but in reality underperformed capability of providing knowledge at the right time and place in tasks 6.2 and 6.3.

5.5.6.1 Use Trade-off Knowledge during Set Narrowing Phase

The following describes how the trade-off curves facilitate the re-use of knowledge in the lean product development environment in order to support the generation of a set of conceptual design solutions. This is based on mapping the initial customer requirements against the pre-defined trade-off curves, as shown in Figure 5.28 (customer requirements are conceptualised for the case of argument in the form of a diamond shape).

Mapping initial customer requirements against the created trade-off curves provides a set of information that will generate a set of design solutions. Such information is based on the decision criteria (explained in Section 5.5.1.5) which could be related to manufacturing process capability, test performance, material and cost as captured amongst the trade-off curves illustrated in Figure 5.28.

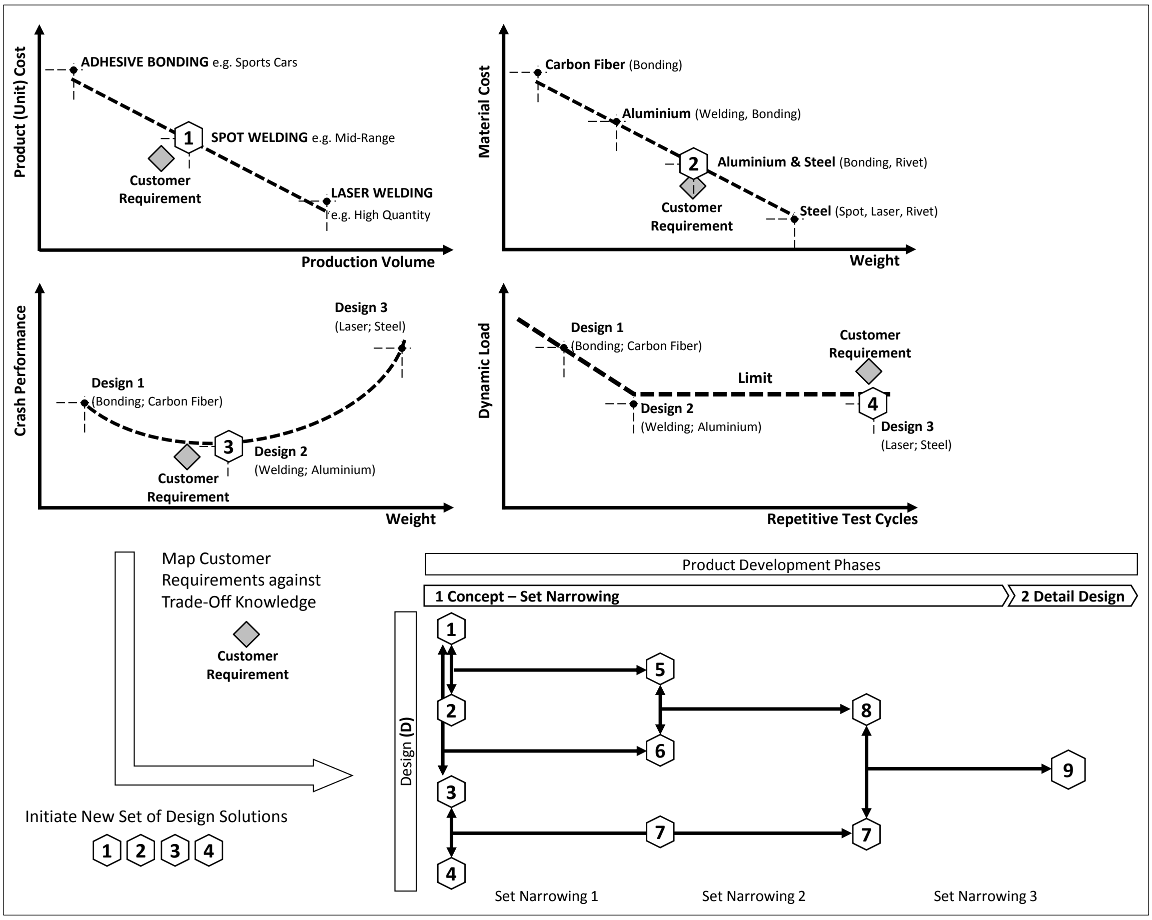


Figure 5.28 Knowledge Use via Trade-Off Curves during Set Narrowing

The mechanism to initiate a set of design solutions results is the inevitable conflict between different trade-off curves to offer an optimum design solution best suitable among certain trade-off variables.

As shown in Figure 5.28, spot welding is the most preferred method in terms of product unit cost and production volume. On the other hand, with regards to crash performance and weight a previous design made from aluminium is ideal. The conflict arises in the fact that aluminium cannot be spot welded. Consequently, such conflict encourages the consideration of multiple design solutions from the early concept phase. In fact there are four potential design solutions, illustrated in Figure 5.28, which represent an initial set of design solutions for the set narrowing phase, as explained in Section 5.3.The author believes that this could stimulate a natural initiation of set based concurrent engineering, which in return requires an underlying process and model to narrow the sets down to reach one final design solution.

5.5.6.2 Establish a Mechanism that Supports Knowledge Provision

In Section 5.5.3.2, regarding knowledge representation using vectors, it was explained how knowledge provision is visually represented in essence by declaring the coordinates where knowledge was created P_{cr}, but more importantly where such knowledge is needed in future P_{nd}.

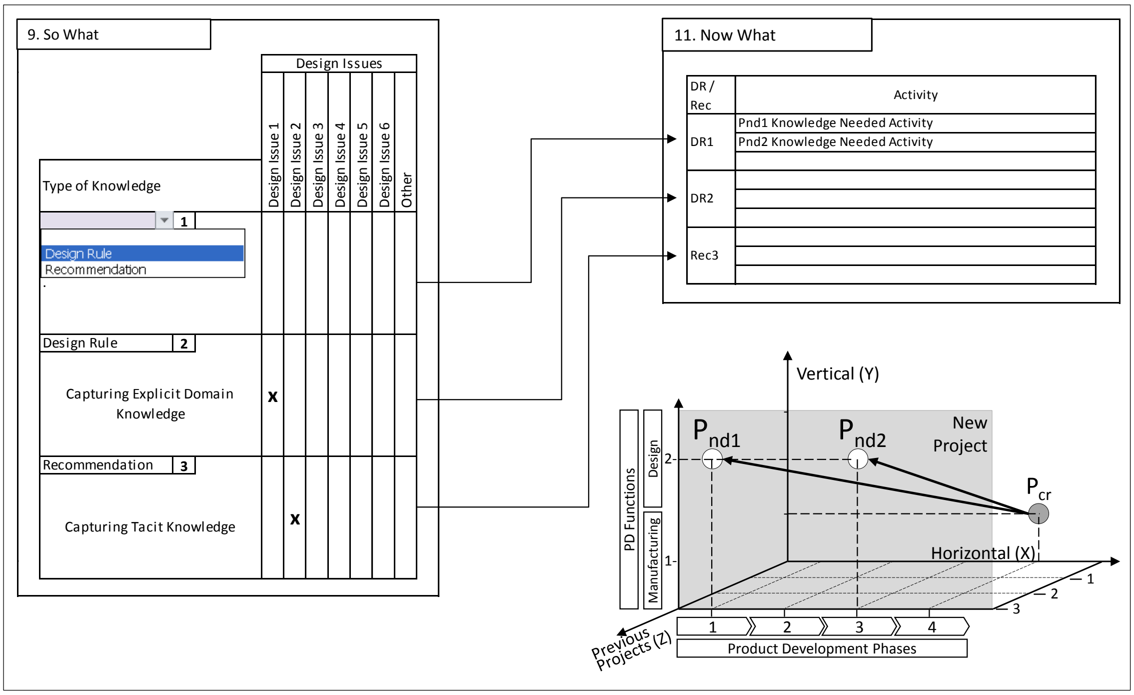


Figure 5.29 Knowledge Provision Mechanism integrated in A3LAMDA template

Given the above the theory and its representation of knowledge provision is established. However, equally important is the activity and mechanism that captures in particular the P_{nd} coordinates from any new knowledge captured in order to provide such knowledge to upcoming activities. In combination with the dynamic knowledge capturing capability enhancement of the A3LAMDA template, knowledge provision was also integrated as an element in the same template, as illustrated in Figure 5.5.

Element number 10 (now what) in the modified A3LAMDA template, was enhanced by including the table, as illustrated in Figure 5.29. Once knowledge is captured in element number 9 (so what), the problem solving team then determines in which activity the captured knowledge is needed in future for every knowledge captured of which represents P_{cr}. Hence, every activity has a unique coordinate within the three dimensions of knowledge baseline line model, as defined in Section 5.5.3.2, undergoing this task results in the declaration of P_{nd} coordinates for the knowledge captured. In other words, every knowledge captured receives the attribute of P_{nd} which was declared by the key stakeholders, product designers and engineers. Hence, this element number 9 (so what) of the A3LAMDA template is linked to the proposed knowledge base structure, as presented in Section 5.5.5.3, any knowledge captured as a result of problem solving entails its knowledge provision coordinates P_{nd} stored in a structured knowledge base.

5.5.6.3 Provide Useful Knowledge at the Right Time and Place

Given the previous task, providing knowledge at the right time and place comprises a continuous comparison of the current product development X-Y coordinates against the knowledge needed P_{nd}, as well as knowledge created P_{cr} X-Y coordinates in the knowledge base. If both coordinates are equal, it means that engineers require the provision of such knowledge at this particular time and place.

As such, it is important to define key product development activities for P_{nd} in particular stage gate reviews such as integration events in order to provide knowledge at key decision stages. Providing the useful knowledge on the other hand is accomplished first of all by providing only adequately rated knowledge, as a result of the feedback score presented in Section 5.5.5.4 and secondly by prioritising knowledge in putting highest rated knowledge forward, as illustrated in Figure 5.30.

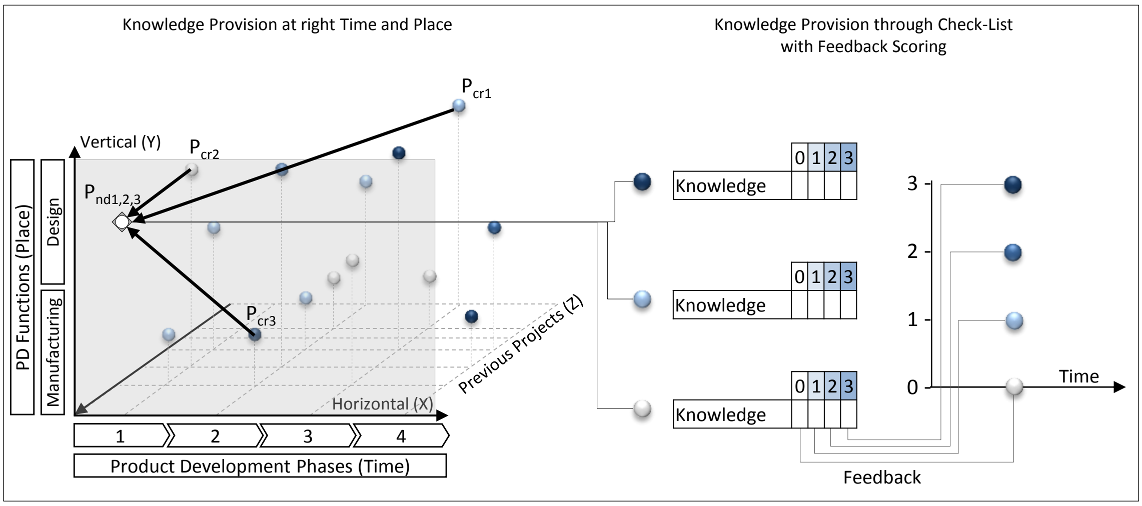


Figure 5.30 Knowledge Provision and Prioritisation

In order to obtain feedback data for future product development, engineers rate the provided knowledge using a Likert scale as illustrated in Figure 5.30. Hence the right form of knowledge provision in the LeanKLC manifests itself with the capability of obtaining feedback values of the provided knowledge. In this way it is possible to acquire a real value over time of the captured knowledge and justify its position within the three dimensions of knowledge management as well as the LeanPD knowledge environment. The author suggests the usage of formal review tools, such as check sheet, decision matrix and design notebook as part of the lean product development toolset, to support standardised knowledge provision at critical time frames. In the scope of this research, the above criteria have been adapted in the use of check list, hence engineers expressed that this method is seen as efficient during the industrial field study mentioned in Section 4.3.

However in reality, as action research progressed it was observed that traditional check lists become overcrowded and out of date. In order to tackle this issue, a check list is suggested capable of capturing the engineer's feedback of the knowledge provided in order to prioritise the knowledge for later reuse, as illustrated in Figure 5.30. This will provide feedback data related to the knowledge provided in a specific activity in product development and as such provide the required scoring to evaluate the feedback value over time, a key knowledge attribute as defined in Section 5.5.3.1.4.

5.6 Managing the Lean Knowledge Life Cycle

The previous sections provided detail of seven LeanKLC stages, 23 tasks as well as their relation to the two elaborated LeanKLC streams A3LAMDA and trade-off curves. This section comprises a reflection on the broad implications of managing the entire LeanKLC to realise a knowledge environment. Hence, Figure 5.31 illustrates the LeanKLC stages with increased visual representation on how the three dimensions of knowledge management in product development build the foundation in the lifecycle of knowledge as a contribution of the work presented research. This was undertaken because it was possible to contextualise the three dimensions of knowledge management in product development with acclaimed LeanPD process models, as explained in Section 5.3.

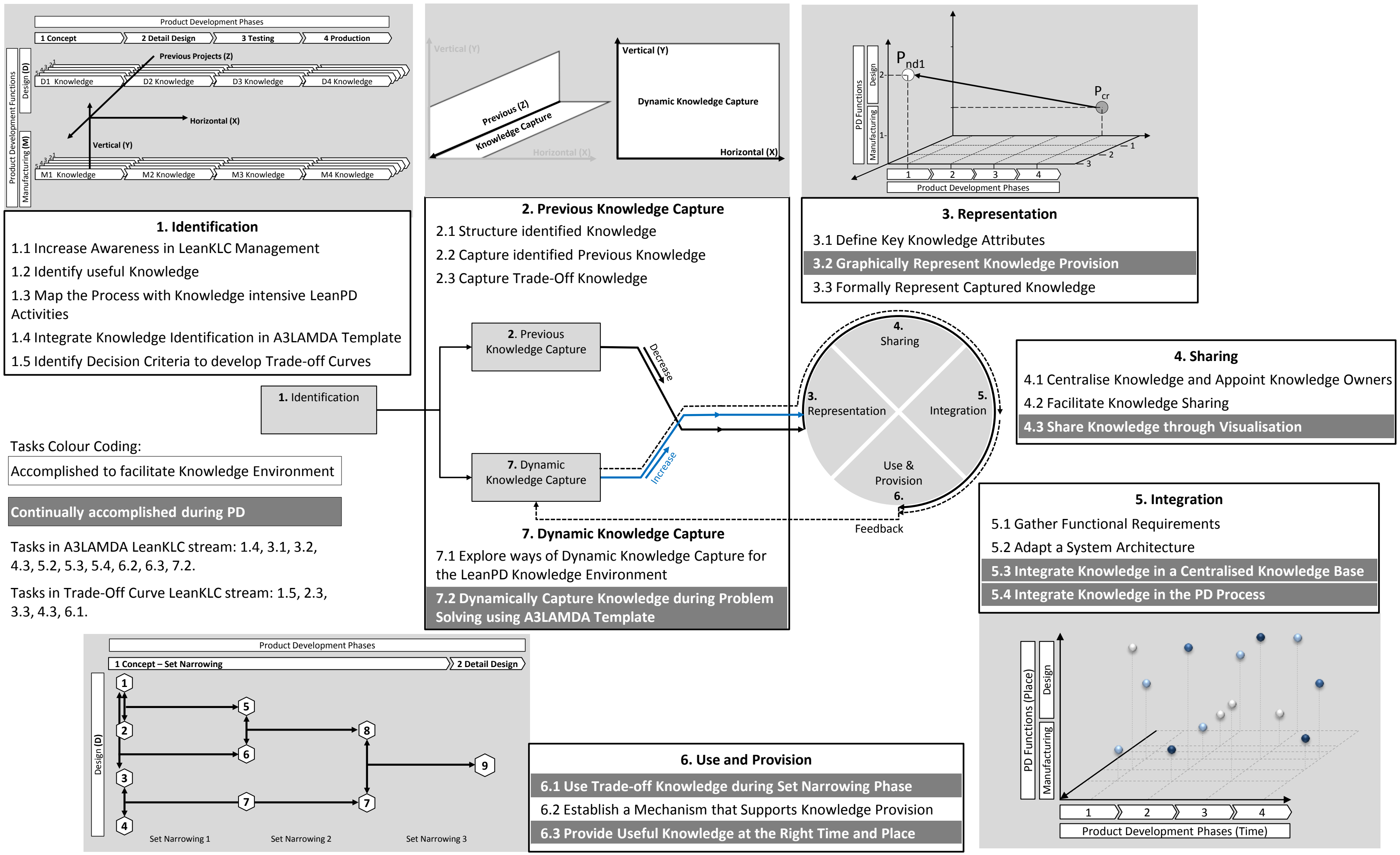


Figure 5.31 Visual Representation of the LeanKLC Framework to Support Lean Product Development

Accordingly, managing the LeanKLC starts in stage 1 with knowledge identification, by providing designers and engineers an increased awareness of the three dimensions of knowledge management in product development as the baseline model of the LeanKLC. With that understanding, stage 2 knowledge capturing concludes two knowledge capturing activities, namely previous knowledge capture in Z dimension and dynamic knowledge capture during the actual product development process in X and Y dimensions. As shown in the centre of Figure 5.31 and explained in Section 5.5.2, previous knowledge capture declines in time whereby dynamic knowledge capture increases to such an extent that it becomes the main priority in the LeanPD knowledge environment. Therefore, the journey towards a knowledge environment in LeanPD is characterised by realising dynamic knowledge capture among its adapted activities.

Knowledge representation in stage 3 comprises the vector representation of knowledge provision within the three dimensions. Stage 4, knowledge sharing, on the other hand, focuses mainly on human interactions as well to facilitate knowledge sharing during LeanPD. Stage 5, knowledge integration, puts knowledge captured in the context of storing and evaluating its usefulness as an integrated element in the LeanPD process. Knowledge use and provision, stage 6, elaborates principles to use trade-off curves knowledge in the set narrowing process as well as providing a method to provide knowledge at the right time, place and format.

The loop of the LeanKLC closes when knowledge used in stage 6 provides a feedback score of usefulness, illustrated in Figure 5.31 as a dotted line, to stage 7, dynamic knowledge capture. Consequently, providing a feedback score allows the capture of new knowledge about the knowledge in re-use. The dotted line collects the feedback for integration which portions and prioritises knowledge use and provision. Given the above knowledge, re-use is not a one off application; moreover it occurs continuously within its re-use lifetime in product development depending on the feedback score captured dynamically from first hand data. This means that the loop for first time LeanKLC application comprises stages 1 to 7. Thereafter, dynamic knowledge capturing takes place by undergoing stages 7 and 3 -6. Once knowledge is captured and is in continuous use and provision it undergoes stages 7, 5 and 6.

Another important aspect, as shown in Figure 5.31, is the separation of those tasks which are accomplished in order to facilitate the creation of a knowledge environment and those that are continually accomplished during LeanPD, as highlighted using grey colour coding. The latter is apparent in stages 3, 4, 5, 6 and 7 and requires enhanced commitment of product development personnel in order to establish ever repeating LeanKLC loops. In order to monitor the long term LeanKLC application the author suggests frequent qualitative assessment of those tasks adapted. A possible assessment method and list of elaborated LeanKLC practices is available in Appendix D.

As presented in Section 5.4 this research set a primary focus of realising two LeanKLC streams in order to provide scalable applications to enhance current PD practices. These are A3LAMDA and Trade-off curves, LeanKLC streams and are explained in the following subsections.

5.6.1 Managing the A3LAMDA LeanKLC Stream

As illustrated in Figure 5.31, the supportive tasks to manage the A3LAMDA LeanKLC stream include tasks 1.4, 3.1, 3.2, 4.3, 5.2, 5.3, 5.4, 6.2, 6.3 and 7.2. The tasks are sequentially arranged to logically correspond to dynamic knowledge capture as well as continuously providing knowledge and collect the feedback value. The final A3LAMDA template as enhanced during this research is shown in Figure 5.32.

The A3LAMDA LeanKLC stream starts with integrating knowledge identification in the A3LAMDA template. Knowledge representation in LeanKLC stage 3 comprises the graphical representation of knowledge provision by declaring key defining knowledge attributes based on the particular LeanKLC application. Knowledge sharing comprises the circulation of A3LAMDA reports in the different periods of completion, as explained in Section 5.5.4.3, as well as undergoing element number 5 (proposed solution) and number 7 (prevent recurrence) in the enhanced A3LAMDA template, as shown in Figure 5.32.

Stage 5 of the LeanKLC comprises the tasks of integrating captured knowledge as a result of problem solving in a centralised knowledge base as well as in the product development process, supported by an underlying system architecture. The proposed knowledge base structure is explained in Section 5.5.5.3, in which the failure documentation section is integrated in the A3LAMDA elements number 1 (team), 2 (background) and 3 (current condition), as illustrated in Figure 5.32.

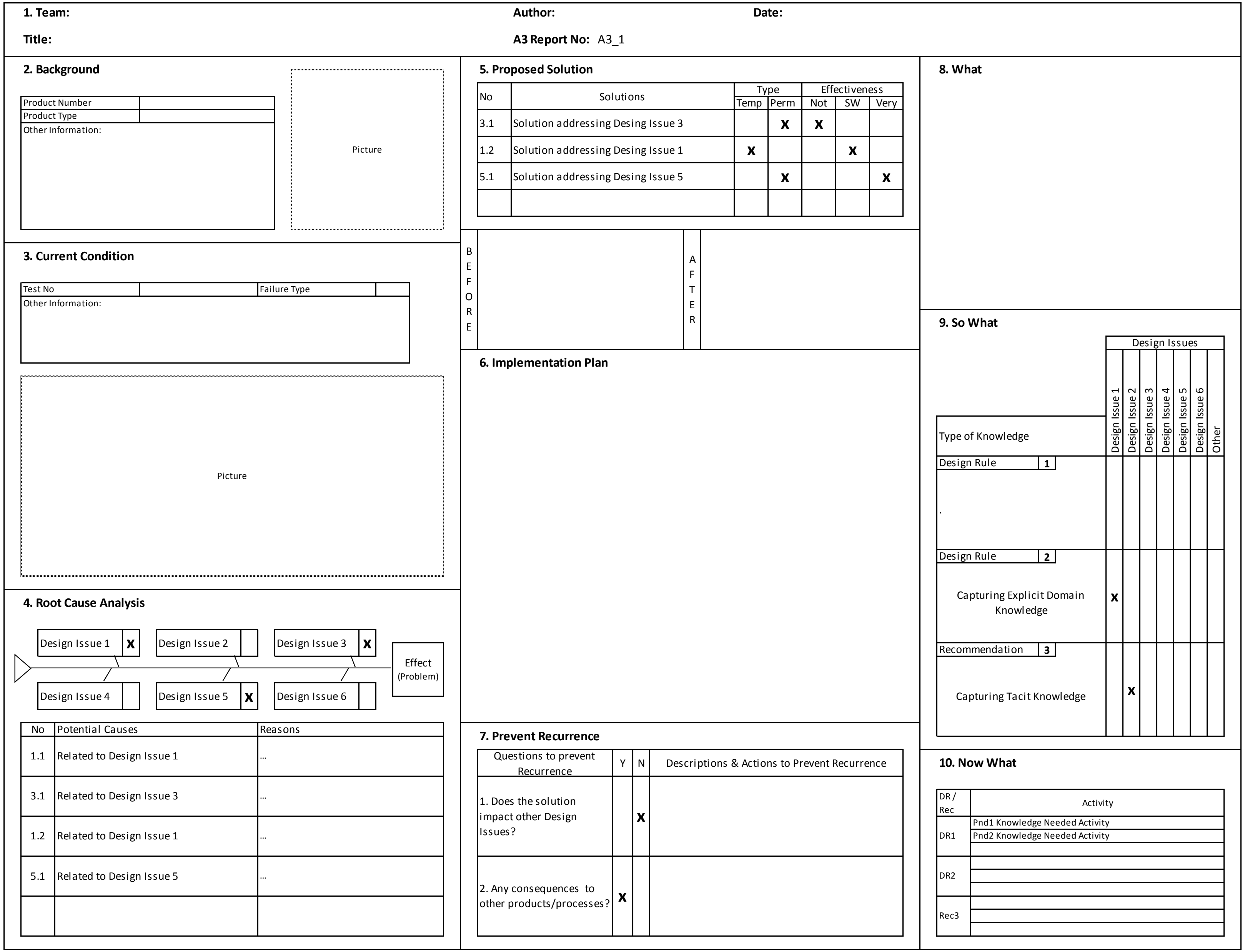


Figure 5.32 A3LAMDA Template developed to support LeanKLC

Knowledge use and provision in LeanKLC stage 6 comprises primarily a front loading mechanism in order to realise the provision of useful knowledge at the right time and place, as well as the mechanism to declare knowledge needed P_{nd} activities for future re-use. Finally, stage 7 comprises the development of a dynamic knowledge capturing element within the A3LAMDA template, such as illustrated in Figure 5.32, element number 9 (so what). As shown in Figure 5.32, element number 6 (implementation plan) and number 8 (what) in the A3LAMDA have not been enhanced during this research; therefore stakeholders have flexibility to design those two elements as seen most suitable for the particular LeanKLC application.

5.6.2 Managing the Trade-off Curves LeanKLC Stream

The trade-off curves LeanKLC stream comprises the tasks 1.5, 2.3, 3.3, 4.3 and 6.1, as marked in Figure 5.31. The Trade-off curves LeanKLC stream starts with knowledge identification by determining the main decision criteria, (Section 5.5.1.5), which directly influences the capturing of trade-off knowledge by depicting the appropriate type of trade-off curve in LeanKLC stage 2, presented in Section 5.5.2.3. Knowledge representation in LeanKLC stage 3 is realised by using formal knowledge representation techniques, in which main attributes are related to the defined trade-off variables from previous tasks in LeanKLC stage 2.

Knowledge sharing in LeanKLC stage 4 occurs by realising the potential of knowledge visualisation via graphical representation as opposed to lengthy reports. Knowledge integration in LeanKLC stage 5 was not thoroughly investigated, because the format of trade-off curves and its usage did not result in huge data sets during the research employed. On the other hand, LeanKLC stage 6 is largely dominated by the use of trade-off curves during the set narrowing phase. The principle, as explained in Section 5.5.6.2, presents the underlying contribution of the LeanKLC to initiate a set of design solutions for set narrowing. As opposed to the A3LAMDA, there is no necessity to undergo collecting feedback; hence trade-off curves are created based on proven knowledge.

5.7 Chapter Summary

This chapter presented two main cornerstones for the development of the LeanKLC; firstly, a baseline model that represented the three dimension of product development knowledge; secondly the synthesising of LeanKLC stages for a lean product development knowledge environment. As a result, the LeanKLC as presented in this chapter provides the framework, stages, tasks and techniques to support the creation of a knowledge environment in lean product development. The LeanKLC is a continuous loop in which new knowledge is captured dynamically as well as already captured knowledge undergoing a continuous loop of integration and provision until its usefulness dissolves. Given the above, the LeanKLC comprises the key research contribution of which application in industry is presented as follows.

Chapter 6

VALIDATION OF THE LEAN KNOWLEDGE LIFE CYCLE

6.1 Introduction

This chapter presents the results of case study validation in order to judge construct validity of the work presented research. Hence, as the LeanKLC is based on a generic baseline model it could have unlimited applications in product development.

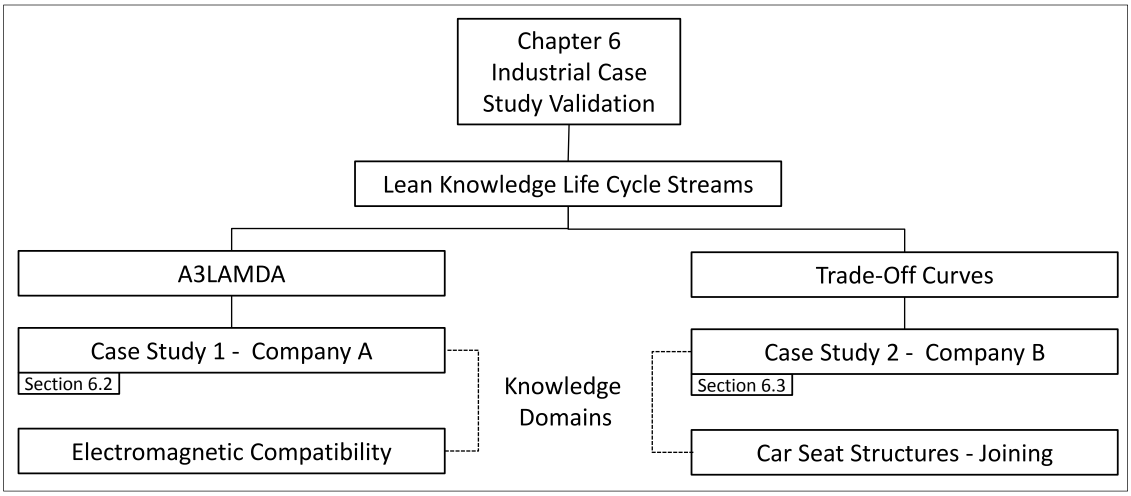


Figure 6.1 Scope of Chapter 6

Therefore the proposed LeanKLC framework is applied among the two knowledge life cycle steams and presented in two different industrial case studies in this chapter by following the instructions as presented in Section 5.5. As shown in Figure 6.1 the two case studies are:

1. The application of the LeanKLC stages based on A3 Thinking for Problem Solving in product development using A3LAMDA template at company A. This is to demonstrate the capability of applying the key stages and tasks of the LeanKLC framework in order to have an effective product design problem solving approach as well as dynamic knowledge capturing and provision. This contributes to the introduction and application of LeanPPD by supporting two of its core enablers: the development of continuous improvement and the creation of a knowledge environment.

2. The application of the LeanKLC by following key tasks of the trade-off curve stream at company B. This aims to demonstrate how real case trade-off curves based on identified decision criteria can be created as well as used to initiate multiple design solutions during set narrowing. In addition, a joint effort with several LeanPPD partners was employed to develop a knowledge based engineering prototype using the key stages of the LeanKLC. Hence, case study 2 will explore two core LeanPPD enablers in company B, namely knowledge environment and set based concurrent engineering.

6.2 Case Study 1: LeanKLC Application in Company A

The application of the LeanKLC in company A was undertaken with a primary focus on the A3LAMDA LeanKLC stream for electromagnetic compatibility (EMC) related design issues. From the total of 23 defined tasks in the LeanKLC framework, 18 have been applied, as illustrated in Figure 6.2 and will be explained as follows.

Lean Knowledge Life Cycle Stages	Tasks accomplished in Case Study One	Tasks supporting A3LAMDA Stream
1. Knowledge Identification	1.1 Increase Awareness in LeanKLC Management to Product Development Personal	
	1.2 Identify useful EMC Knowledge	
	1.3 Map the Process with Knowledge intensive LeanPD Activities during EMC Product Design	
	1.4 Integrate EMC Knowledge Identification in A3LAMDA Template	X
2. Previous Knowledge Capture	2.1 Structure identified EMC Knowledge	
	2.2 Capture identified Previous EMC Knowledge	
3. Knowledge Representation	3.1 Define Key EMC Knowledge Attributes	X
	3.2 Graphically Represent EMC Knowledge Provision during New Product Development	X
4. Knowledge Sharing	4.1 Centralise EMC Knowledge	
	4.2 Facilitate EMC Knowledge Sharing	
	4.3 Share EMC Knowledge through Visualisation	X
5. Knowledge Integration	5.1 Gather Functional Requirements for LeanKLC application in Company A	
	5.2 Adapt a System Architecture for LeanKLC application in Company A	X
	5.3 Integrate EMC Knowledge in a Centralised Knowledge Base	X
6. Knowledge Use and Provision	6.2 Establish a Mechanism that Supports EMC Knowledge Provision	X
	6.3 Provide Useful EMC Knowledge at the Right Time and Place	
7. Dynamic Knowledge Capture	7.1 Explore ways of Dynamic EMC Knowledge Capture for the LeanPD Knowledge Environment	
	7.2 Dynamically Capture Automotive EMC Knowledge during Problem Solving using A3LAMDA Template	X

Figure 6.2 LeanKLC application at Company A

The product development process in company A comprises three phases, namely concept, detail design and testing, as shown in Figure 6.3. During the concept phase an electrical architecture is created illustrating the wiring of the required components. The detail design phase contains the necessary activities to design and develop a physical product. Testing comprises the verification or validation of the physical product in order to conform to the EMC customer requirements.

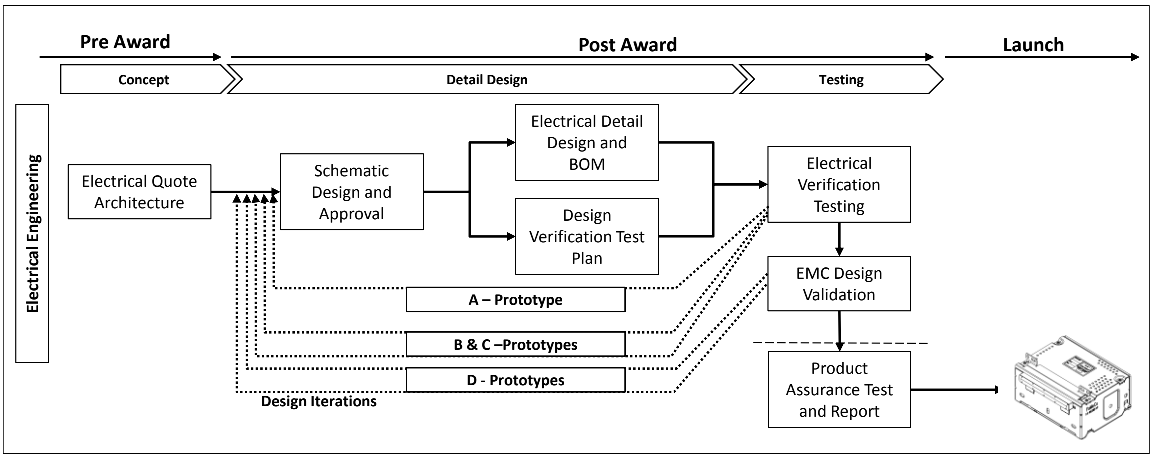


Figure 6.3 Electromagnetic Compatibility related Design Iterations

Verification is undertaken frequently during product development by improving the proposed design solution (A, B and C prototypes) until reaching the confidence to pass the entire EMC test requirements. Validation on the other hand is performed under standard and certified procedures on final design solutions (D prototypes). However, design iteration caused by not passing the EMC requirements during verification and validation are costly and time consuming. Moreover, automotive EMC test requirements (Ford, 2009) are sophisticated and details of test arrangement differ among automotive OEMs. The main EMC test types defined by electrical engineers in company A are:

1. Radiated Emissions (RE)
2. Conducted Emission (CE)
3. Radiated Immunity (RI)
4. Conducted Immunity (CI)
5. Electrostatic Discharge (ESD).

Emissions and immunity requirements apply within radiated (RE and RI) and conducted (CE and CI) spectrums. Emissions (RE and CE) of a developed product are required not to exceed a limit given by the customer in order not to cause interference to other electrical or electronic units in the car.

The immunity requirements (RI and CI) on the other demands of a product to function (be immune) during radiated and conducted interferences caused by surrounding electrical objects. Electrostatic discharge comprises the capability of a product to withstand its related interference during handling by operators as well as during normal operation under powered condition. However, preventing EMC failure is unpredictable due to the fact that occasionally phenomena occur without the possibility of explaining its cause, hence making electrical engineers highly dependent on their own tacit knowledge.

6.2.1 Knowledge Identification: Stage 1 of the LeanKLC in Case Study 1

Task 1.1 Increase Awareness in LeanKLC Management to Product Development Personal

This task was accomplished via industrial workshops in focus group settings. The initial workshop was undertaken with two continuous improvement engineers to agree that the LeanKLC is a suitable framework to provide the right knowledge environment for the EMC knowledge domain. Then, three workshops were followed with a group of EMC application engineers in order to increase awareness among key stakeholders as well as elaborate a suitable A3LAMDA template.

Finally, one workshop with eleven product development designers and engineers was accomplished to promote problem solving using the A3LAMDA approach among the multidisciplinary problem solving team.

Table 6.1 Outcomes of Increase Awareness Task in Case Study 1

Task 1.1 Outcome	Detail
Objective	Apply the novel LeanKLC in order to realise dynamic knowledge capturing and provision resulting from EMC design problem solving
Scope	EMC design problems triggered in the electrical engineering function: - 80% of product design problems to be solved intuitively - **15%** of product design problems to be documented in **new A3LAMDA report** - 5% of product design problems to be documented in current 8D report
Definition of Knowledge	Any form of solutions to prevent an EMC test failure
Research Duration	14 months
Human Resources	- Eight engineers to participate in open questionnaire sessions to identify useful knowledge - Two EMC application engineers as A3LAMDA authors to guide problem solving in a multidisciplinary team

The main outcome with regards to objective, scope, definition of knowledge, research duration and human resources of the LeanKLC application in case study 1 is illustrated in Table 6.1.

Task 1.2 Identify useful EMC Knowledge

Task 1.2 included in depth face to face meetings with eight engineers to locate existing sources of EMC knowledge using open questions, of which the key findings are summarised in Table 6.2.

Table 6.2 EMC Knowledge Identification Key Findings on selected open Questions

Open Questions	Key Findings
Where does knowledge exist?	- Tacit knowledge is main source of knowledge when considering EMC in the product design
How it was captured before?	- Initiative 1 / Source 1 - Initiative 2 / Source 2 - Initiative 3 / Source 3 - Imitative 4 / Source 4
What knowledge does the product designer or engineer need?	- Knowledge that will ensure that previous EMC design problem won't recur

Although several initiatives attempted to capture EMC knowledge, currently product development engineers mainly rely on tacit knowledge when considering EMC in the product design. The knowledge needed applies to the sources of knowledge that will prevent the recurrence of previous EMC failures.

Task 1.3 Map the Process with Knowledge intensive LeanPD Activities during EMC Product Design

Process mapping was undertaken using work flow diagram techniques to present the current As-Is (Figure 6.4-a), as well as the envisioned knowledge environment To-Be accomplished through LeanKLC application (Figure 6.4-b).

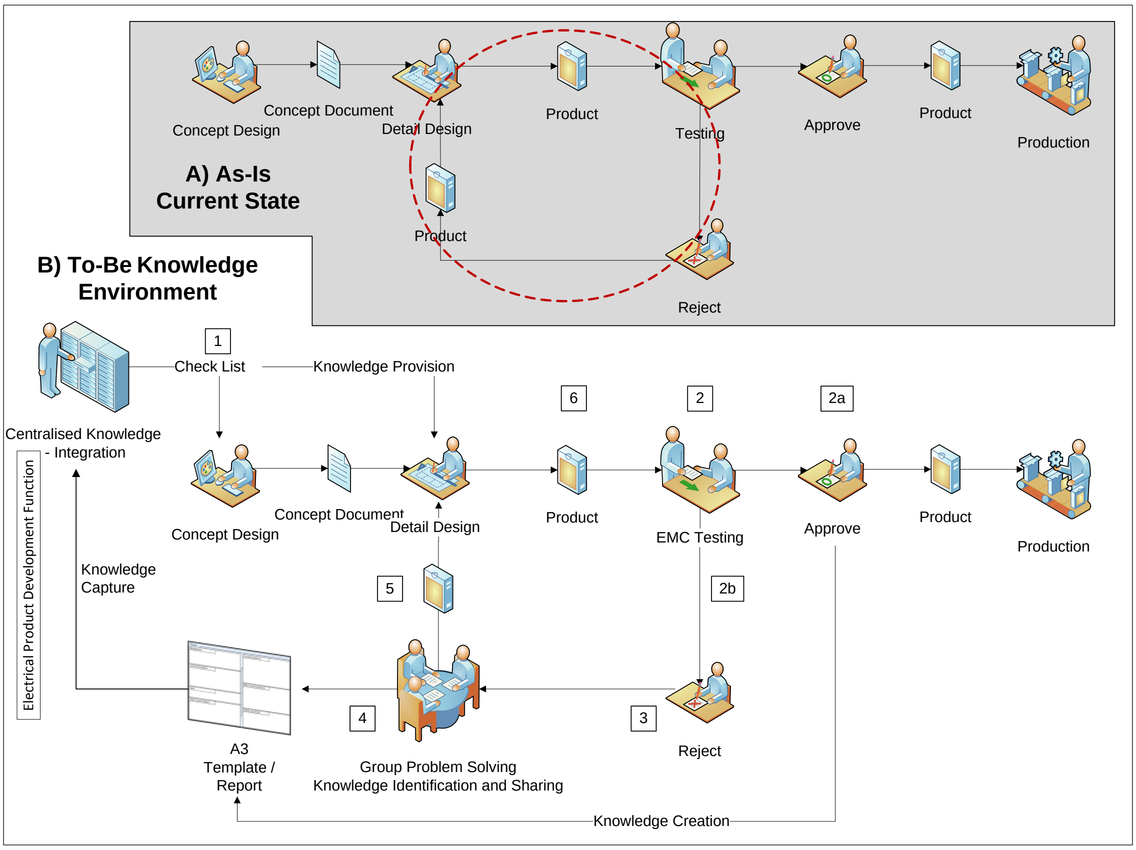


Figure 6.4 EMC As-Is and To-Be Workflow Diagram in Company A

In order to realise the To-Be knowledge environment during product development, the following describes the key activities aligned with the sequential order, as shown in Figure 6.4-b.

1. During concept and detail design the electrical product development engineers receive check lists in order to ensure that previous failures are not repeated.

These check lists include knowledge provision guiding the engineers to successfully pass the EMC tests.

2. During EMC testing two conditions are possible: the product either a) passes or b) fails.
    a. Products that pass the test are documented in order to know in future which design configurations are likely to pass the EMC test.
    b. Products that fail the test go back to detail design for rework and undergo the activities of group problem solving.
3. Problem Solving starts with the failure documentation, where the test engineers define the exact EMC failure mode and inform electrical detail design.
4. Problem solving is undertaken as a group exercise preferably in multifunctional teams using the A3LAMDA template. This activity facilitates knowledge sharing and moreover knowledge identification during root cause analysis.
5. Once a solution to a problem is found the product is modified by detail design.
6. Finally, the modified product undergoes retesting. If the product passes the test it means that the solution is verified. Consequently, new knowledge is created, documented in the A3LAMDA report and stored in the centralised knowledge base. However, if the part is failing the test the process is repeated from activity 3 until a solution is found.

Task 1.4 Integrate EMC Knowledge Identification in A3LAMDA Template

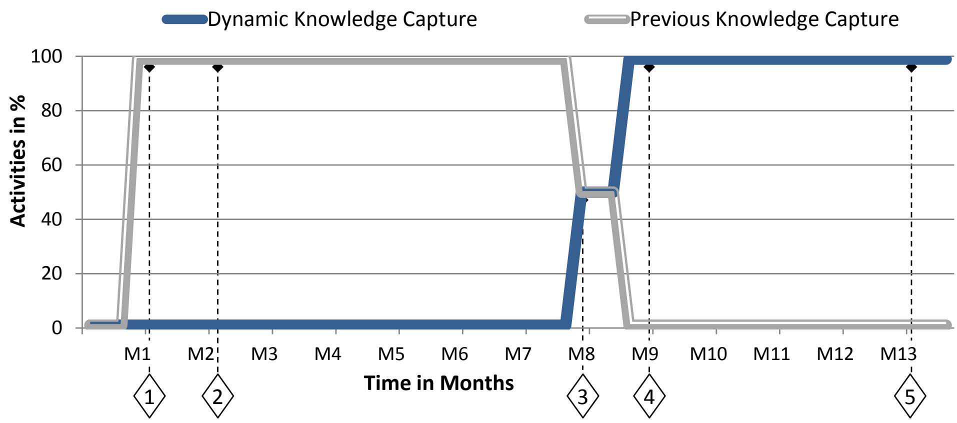
During previously explained knowledge identification tasks 1.1, 1.2 and 1.3, six design issues have been raised by the engineers as the most apparent root cause categories during EMC design problem solving, these being:

1. Circuit Design
2. Printed Circuit Board (PCB) Layout
3. Software
4. Interface
5. Enclosure
6. Test Issues.

These have been represented throughout all A3LAMDA templates by means of potential design issues in element number 4, namely root cause analysis, as illustrated in Figure 6.7.

6.2.2 Knowledge Capture: Stages 2 and 7 of the LeanKLC in Case Study 1

The activities and milestones with regards to previous and dynamic knowledge capture during the 14 month research duration in case study 1 is illustrated in Figure 6.5. The first six months of the LeanKLC application comprised the capturing of previous EMC knowledge as identified in task 1.2, as well as completing two A3LAMDA pilot-reports to familiarise the key stakeholder with the new form of problem solving and more importantly, knowledge capturing.



No.	Knowledge Capture Activities at Milestone during Case Study one
1	Previous EMC knowledge capture from knowledge sources as identified in Task 1.2 (section 6.2.1)
2	Two A3LAMDA pilot-reports documented from previous problem solving activities
3	PD Engineers use A3LAMDA templates to dynamically capture EMC knowledge during current projects
4	Dynamic EMC knowledge capture using A3LAMDA templates evolves to prime activity
5	Six A3LAMDA reports completed by PD engineers

Figure 6.5 EMC Knowledge Capture activities during Case Study 1

The transition into dynamic knowledge capture occurred in month seven at milestone three, as shown in Figure 6.5, when electrical engineers used the A3LAMDA template to solve problems during actual product development projects. The tasks as undertaken for the knowledge capture stages two and seven of the LeanKLC are explained as follows.

Task 2.1 Structure identified EMC Knowledge

As there was no apparent systematic and up to date approach for capturing EMC knowledge, knowledge was structured most suitably for the LeanKLC application in case study 1.

Task 2.2 Capture identified Previous EMC Knowledge

The capturing of identified previous knowledge from the identified sources in task 1.2 resulted in 55 EMC related recommendations, which have been stored in the knowledge base as put forward in Section 6.2.5. However, lack of essential information such as details of knowledge needed P_{nd} attributes limits the re-use of such recommendations. Nevertheless, the researcher did not demand more information on the captured knowledge, as it could have demotivated electrical engineers in the early stage of the LeanKLC. Instead, the involvement of electrical engineers has been shifted to participate mainly in dynamic knowledge capture activities using the A3LAMDA template, which provides a major contribution to the envisioned knowledge environment. For this reason two A3LAMDA pilot-reports have been completed based on problems solved in the past, which can be seen in Appendix D.

Task 7.1 Explore ways of Dynamic EMC Knowledge Capture for the LeanPD Knowledge Environment

This task followed the key principles to realise dynamic knowledge capturing for the LeanKLC application in case study 1 and is explained as follows.

a) Establish a method were engineers are motivated to participate

During increase awareness task 1.1, future stakeholders agreed that knowledge resulting from problem solving is vital and that A3LAMDA provides an adequate approach.

b) Integrate knowledge capturing in the product development process

Knowledge capturing as an integrated part of the problem solving activity in order to support engineering decision making in future product design projects.

c) Facilitate a process that captures knowledge whilst created

This has been accomplished by providing electrical engineers with an interface to complete an A3LAMDA template and its associated dynamic knowledge capture in electronic form using Microsoft Excel. As engineers at company A are used to this software, engagement in the dynamic knowledge capturing process did not require extensive training to complete an A3LAMDA report. Moreover, conditional formatting was used to facilitate data entry by highlighting incomplete elements of the A3LAMDA report in purple colour, as illustrated in Figure 6.3.

d) Minimise documentation effort

The developed A3LAMDA template in Excel included drop down selection and interlinked cells in order to minimise documentation effort, as illustrated in Figure 6.6.

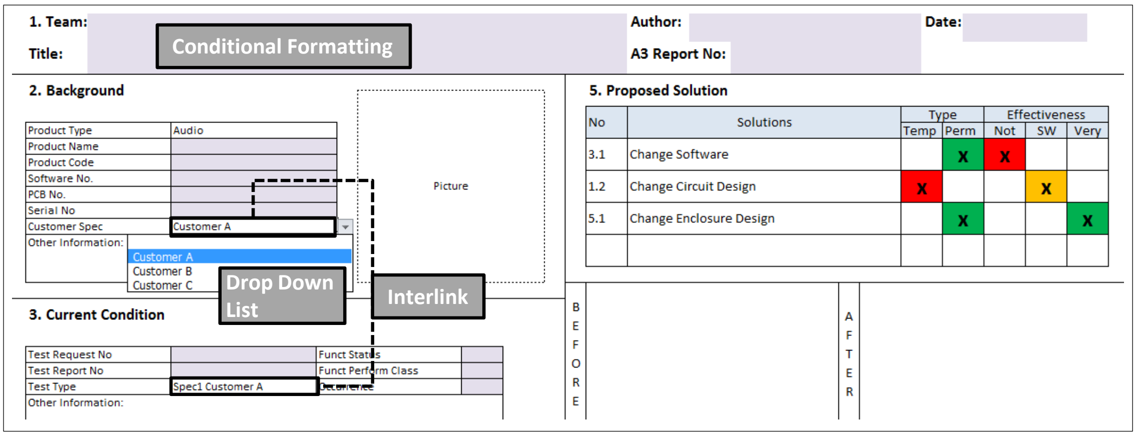


Figure 6.6 Facilitating Elements to realise EMC Dynamic Knowledge Capture using Microsoft Excel Interface

Cells which require standard data input have been represented as drop down lists, such as selecting particular customer specifications. Interlinked cells facilitate the documentation where duplicate information is required or when there is a logical sequence between the cells. As shown in Figure 6.6, when the engineer chooses a customer specification in element number 2 (background) in the A3LAMDA template, the type of test drop down list in element number 3 (current condition) changes accordingly, as there are different affiliations among customers.

e) Enhance current techniques of the LeanPD knowledge environment to accomplish this task

A3 thinking and LAMDA learning cycle are two techniques largely discussed in the LeanPD community. The final A3LAMDA template in electronic form using Excel as put forward in case study 1 is illustrated in Figure 6.7 and provides entry cells for knowledge created in the form of design rules or recommendations in element number 9 (so what).

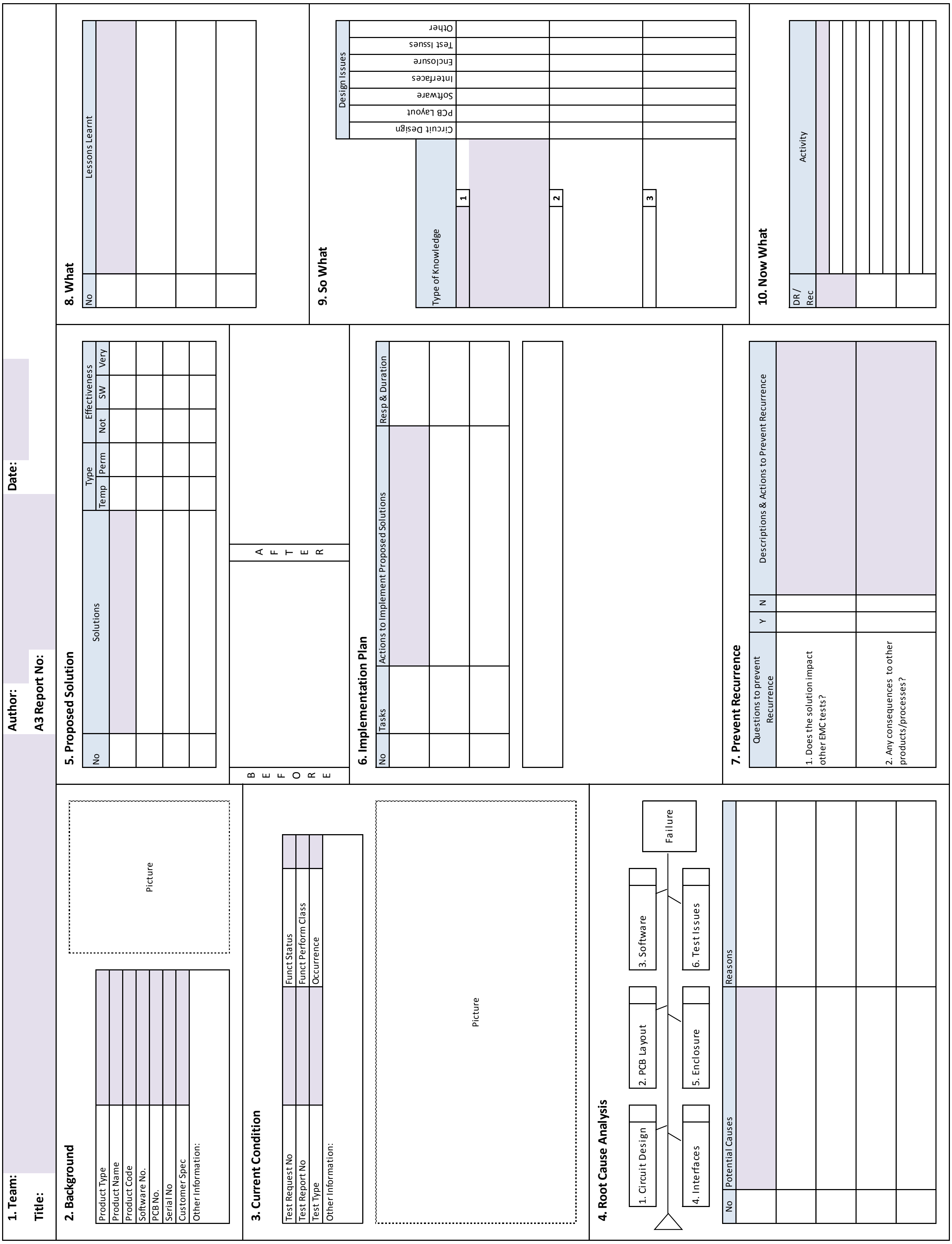


Figure 6.7 Excel Version of the A3LAMDA Template to realise EMC Dynamic Knowledge Capture

Task 7.2 Dynamically Capture Automotive EMC Knowledge during Problem Solving using A3LAMDA Template

Dynamic knowledge capturing was performed by electrical engineers independently using the provided A3LAMDA Excel templates on current product development projects to solve EMC design problems. As shown in Figure 6.8, six A3LAMDA reports were completed to solve EMC design problems during particular product development projects. A3LAMDA reports number 2 and 3 were performed within the same project number two.

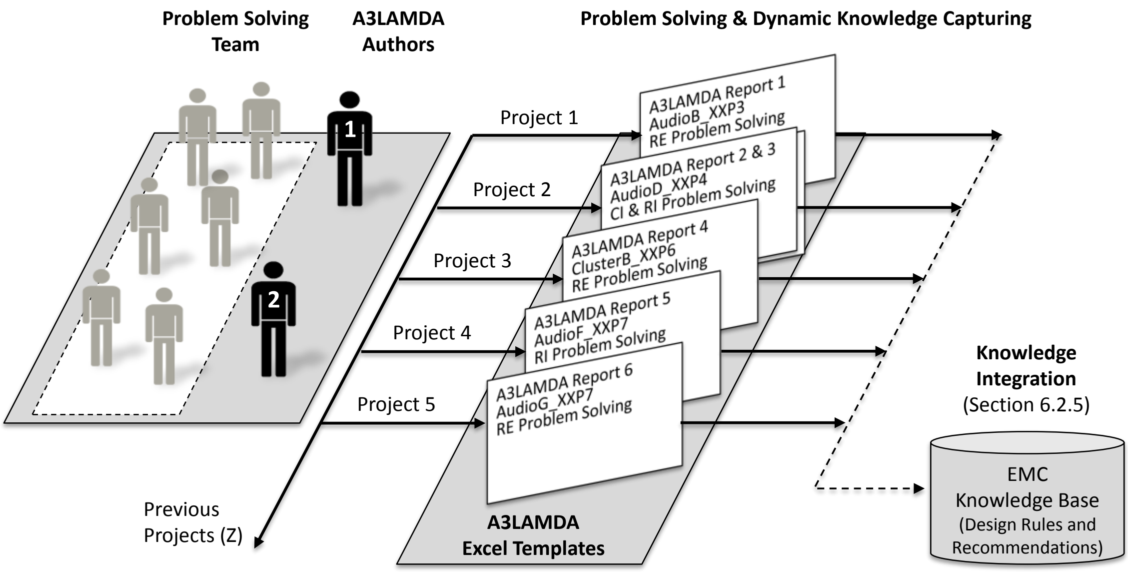


Figure 6.8 Dynamic Knowledge Capturing at Company A related to EMC Product Design Problem Solving

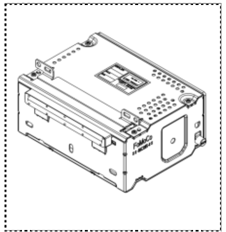
Whilst the problem solving activities were undertaken in cross-functional teams, the initiation and documentation of A3LAMDA reports was carried out by two authors, both EMC application engineers. As shown in Figure 6.8, five A3LAMDA reports entailed problem solving activities related to audio products and one related to instrument clusters. With regard to EMC test failures, three reports entail radiated emissions (RE), one conducted immunity (CI) and two radiated immunity (RI) related tests. Figure 6.9, Figure 6.10, Figure 6.11, Figure 6.12, Figure 6.13 and Figure 6.14 below illustrate the A3LAMDA reports as independently completed by the electrical engineers in order to solve EMC design problems as well as capture the created knowledge whilst created. Moreover, it is a step change in product development knowledge management, as this case study is presenting for the first time evidence of dynamic knowledge capture.

1. Team: PA, IP, MS, CC, RR **Author:** MS **Date:** 01/12/2011

Title: Class D Rod Antenna RE failure **A3 Report No:** A3R1

2. Background

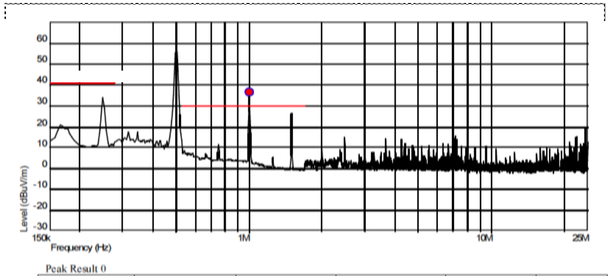
Product Type	Audio
Product Name	AudioB
Product Code	XXP3
Software No.	XXS3
PCB No.	XXPCB3
Serial No	XX3
Customer Spec	A
Other Information:	



3. Current Condition

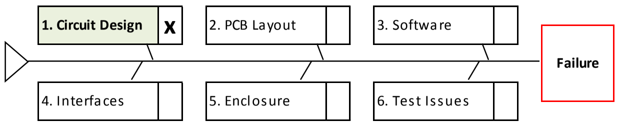
Test Request No	XTRQ3	Funct Status	II
Test Report No	XTRP3	Funct Perform Class	A
Test Type	RE XX	Occurrence	1
Other Information: Same failure for MP3, FM, AM, DAB			

Rod antenna is failed the radiated emissions



Frequency(Hz)	Level(dBuV/m)	Limit(dBuV/m)	Margin(dBuV/m)	Detector	RBW(Hz)
1.002 M	36.47	30.00	6.47	PEAK CISPR	9.0k

4. Root Cause Analysis

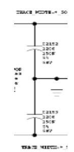


No	Potential Causes	Reasons
1.1	Class-D Amp (Confirmed by freq change)	
1.2	Could be on power wires	
1.3	Could be speaker cables	

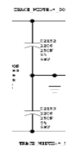
5. Proposed Solution

No	Solutions	Type		Effectiveness		
		Temp	Perm	Not	SW	Very
1.1	Spread spectrum on clock		X	X		
1.2	Changes to power supply filter to Class-D Amplifier		X	X		
1.3	Change to Class-D output filters. CY, CX to 1uF		X		X	

BEFORE



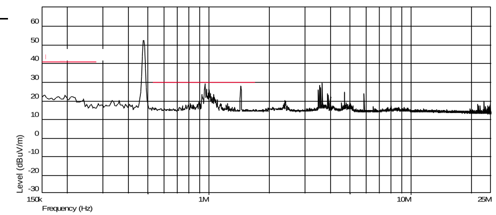
AFTER



6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
1.3.1	Update design	Change schematic, BOM	CC
1.3.2	Verify changes	Development testing	MS
1.3.3	Formal Testing	MoC, Raise new TR, update samples	RR

Result: The diagram shows the comparison results where the RE for rod antenna is under limit = 25MHz.



7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?	X		MoC XXYYZZ Check on Audio output quality/output power Retested as TR.XXX
2. Any consequences to other products/processes?		X	

8. What

No	Lessons Learnt

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation 1							
Class-D Output Low Pass filter should have low enough cut-off to reduce amplitude of switching frequency and harmonics.	X						
Recommendation 2							
Testing needs to ensure that all outputs fully exercised.						X	
3							

(Design Issues: Circuit Design, PCB Layout, Software, Interfaces, Enclosure, Test Issues, Other)

10. Now What

DR / Rec	Activity
Rec1	Schematic Design and Approval (41)
Rec2	Develop Hardware Test Plan, ADVP, DVP (62)

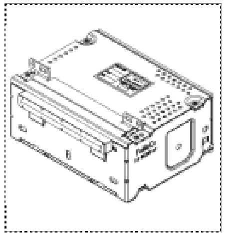
Figure 6.9 A3LAMDA Report 1 documented during RE Problem Solving in Project 1

1. Team: MS, SB and LG **Author:** MS **Date:** 03/01/2012

Title: CI XX MP3 mode failure **A3 Report No:** A3R2

2. Background

Product Type	Audio
Product Name	AudioD
Product Code	XXP4
Software No.	XXS4
PCB No.	XXPCB4
Serial No	XX4
Customer Spec	A
Other Information:	



3. Current Condition

Test Request No	XTRQ4	Funct Status	II
Test Report No	XTRP4	Funct Perform Class	A
Test Type	CI XX	Occurrence	1

Other Information: Test specification allows for the reflection of mode after CI XX test.

Description of failure: CI XX MP3, Eject and re-insert disc required to continue operation.

4. Root Cause Analysis

1. Circuit Design X
2. PCB Layout
3. Software
4. Interfaces
5. Enclosure
6. Test Issues

CI XX MP3 mode failure

No	Potential Causes	Reasons
1.1	Test technician did not identify recovery method as per test plan.	Order of recovery sequence not define in test plan.
1.2	Software by causing issues with mechanism reset.	it is possible that the power interference causes the lock-up. No evidence fails for this.

5. Proposed Solution

No	Solutions	Type: Temp	Type: Perm	Effectiveness: Not	Effectiveness: SW	Effectiveness: Very
1.1	Recover operation by selecting operation modes. This is in the layout test plan.		X			X

BEFORE

AFTER

6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
1.1.1	Re-Test	Testing already done as part of investigation	Test lab - 1 day

Result: Test set up issue, after re-test it shows that it is not a failure

7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?		X	
2. Any consequences to other products/processes?		X	

8. What

No	Lessons Learnt
1	Something a reported it is not necessarily a failure.
2	if the recovery method fron the CI event is not properly defined, technician doesnt know what to do.

9. So What

Type of Knowledge		Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation	1							
EMC test plan clearly defines recovery sequence after immnunity events.								X
	2							
	3							

(Design Issues: Circuit Design, PCB Layout, Software, Interfaces, Enclosure, Test Issues, Other)

10. Now What

DR / Rec	Activity
Rec1	Support EMC Design Validation (53)
	Develop Hardware Test Plan, ADVP, DVP (62)
	Test and Report (58)

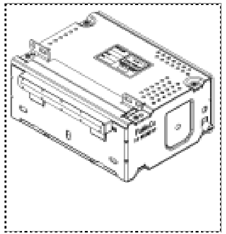
Figure 6.10 A3LAMDA Report 2 documented during CI Problem Solving in Project 2

1. Team: MS, CC, RL, RW, IP, PB **Author:** MS **Date:** 27/02/2012

Title: DAB RI XX failure **A3 Report No:** A3R3

2. Background

Product Type	Audio
Product Name	AudioD
Product Code	XXP4
Software No.	XXS4
PCB No.	XXPCB4
Serial No	XX4
Customer Spec	A
Other Information:	



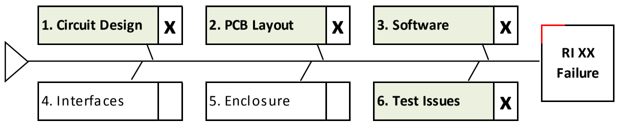
3. Current Condition

Test Request No	XTRQ5	Funct Status	II
Test Report No	STRP5	Funct Perform Class	A
Test Type	RI XX	Occurrence	2
Other Information: Failure occurs only for interference applied for >15seconds. Self recovery seen for interference to 2s.			

e-mail from Phil Bailey :

Results obtained show that the audio drops out but recovers with a 2 second dwell at 580-610MHz and 720-760MHz. When a longer dwell time is used due to our thresholding routine the DUT does not self-recover. The Customer A requirement is for a minimum dwell time of 2 seconds , longer dwell times may be necessary if DUT function response times are expected to be longer.

4. Root Cause Analysis



No	Potential Causes	Reasons
1.1	SPI interface to DAB module vulnerable to interference	Failure consistent with SPI communication failure. Issue not seen on DAB on Main Board variant with different filtering.
2.1	Layout issues on SPI lines	Layout is different to DAB on main board design.
3.1	Software does not handle SPI errors gracefully	Return to FM mode is consistent with DAB source being deallocated.
6.1	Field being applied too long due to auto-thresholding.	If field is only applied for 2s, self recovery is seen.

5. Proposed Solution

No	Solutions	Type: Temp	Type: Perm	Effectiveness: Not	Effectiveness: SW	Effectiveness: Very
1.1	Change filtering on VX to be similar to that on DAB on main board.			X		
2.1	Review and change layout if appropriate. (No changes yet identified)					
3.1	Modify software to stop communications to DAB module while SPI errors seen. (Not tried)					
6.1	Change test procedure to do non-audio test for level 2 so interference not applied for as long as 15s.	X				X

BEFORE	AFTER
Unit drops to FM mode for 580-610MHz and 720-760MHz at Level 2. Typical thresholds at 80-90V/m	DAB Audio signal drops out but self recovers.

6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
1.1.1	re-test	(Testing already done as part of investigation)	Test lab
6.1.2	document test process change	e-mail to test labs from EMC application engineer	MS - 1 day.

Ideally would explore more permanent solution. Temporary solution deemed low risk as interference at this level in the vehicle is unlikely.

7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?	X		Same test process applied to all audio products Need to ensure that real underlying issues are identified.
2. Any consequences to other products/processes?		X	

8. What

No	Lessons Learnt
1	Need to consider effect of longer periods of interference. And specify in test plan if required.
2	Need to pay special attention to immunity of SPI interfaces.
3	Software should deal with corruption on internal interfaces gracefully, recovering to previous mode where possible.

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation 1: Specify in EMC test plan whether it is necessary to apply field for longer than the 2s minimum						X	
Recommendation 2: Review SPI interface for vulnerability to radiated fields.	X						
Recommendation 3: Review software for graceful handling of eroors on internal interfaces			X				

10. Now What

DR / Rec	Activity
Rec1	Develop end of line test parameters (54)
Rec2	Schematic Design and Approval (41)
Rec3	Software Detail Design (104)

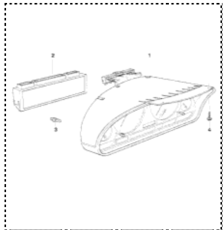
Figure 6.11 A3LAMDA Report 3 documented during RI Problem Solving in Project 2

1. Team: KG and AK **Author:** AK **Date:** 03/03/2012

Title: Measurement of Magnetic Radiated Emissions **A3 Report No:** A3R4

2. Background

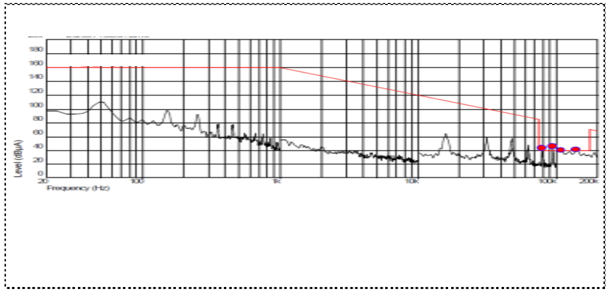
Product Type	Instrument Cluster
Product Name	ClusterB
Product Code	XXP6
Software No.	XXS6
PCB No.	XXPCB6
Serial No	XX6
Customer Spec	B
Other Information:	



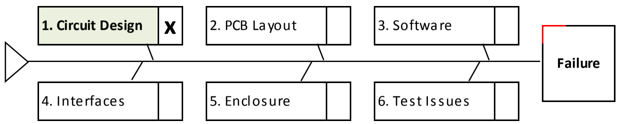
3. Current Condition

Test Request No	XTRQ6	Funct Status	I
Test Report No	XTRP6	Funct Perform Class	A
Test Type	RE XX	Occurrence	2

Other Information: The loop antenna is positioned on the rear RHS of the cluster and the emissions at 78.8kHz and 94.4kHz fail the limit line



4. Root Cause Analysis

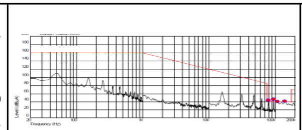


No	Potential Causes	Reasons
1.1	Speaker	Magnetic coil of speaker. (IT'S NOT THE SPEAKER AS THIS IS NOT DRIVEN)
1.2	Telltales	Current in tracks is at least 12mA.
1.3	Stepper Motors	Current in tracks at least 20mA.
1.4	Illumination	20mA in each LED branch of 11 branches.

5. Proposed Solution

No	Solutions	Type: Temp	Type: Perm	Effectiveness: Not	Effectiveness: SW	Effectiveness: Very
1.1	The Y spec is less than 40dBuA/m whereas the X spec requires 60dBuA/m.	X		X		
1.3	The mode of operation change to COMFORT mode where the tell tales and motors are not driven		X		X	

BEFORE



AFTER

6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
1.3	Re-test	Change the mode of the cluster during the test.	EMC Test Engineer

7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?		X	
2. Any consequences to other products/processes?	X		The limit line from the X specification should be used and the mode of testing should be COMFORT mode for EQ.XXX.

8. What

No	Lessons Learnt
1	The lesson to be learnt is that during the pre-DV the test was NOT done correctly as only the front face was tested. If we had this information earlier then we would have discussed this with Customer B before validation started and we would have negotiated tesing to the X spec requirements.

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation 1							
The pre-DV test must be correctly and fully performed before validation.	X						
2							
3							

(Columns Circuit Design to Other are headed "Design Issues".)

10. Now What

DR / Rec	Activity
	Test Go/NoGo Decision (85)
Rec1	Develop Verification Test Plans (49)

Figure 6.12 A3LAMDA Report 4 documented during RE Problem Solving in Project 3

1. Team: MS **Author:** MS **Date:** 23/04/2012

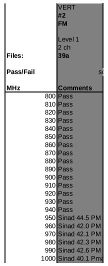
Title: Radio Band 5A Radiated Immunity issues. **A3 Report No:** A3R5

2. Background

Product Type	Audio
Product Name	AudioF
Product Code	XXP7
Software No.	XXS7
PCB No.	XXPCB7
Serial No	XX7
Customer Spec	C
Other Information:	

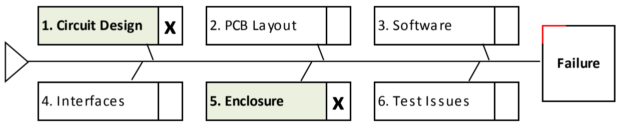
3. Current Condition

Test Request No	XTRP7	Funct Status	II
Test Report No	XTRQ8	Funct Perform Class	A
Test Type	RI XX	Occurrence	3
Other Information:			



SINAD (Audio degradation seen for one sample only (#2) in band 5A, 950-1000MHz. Issue seen in FM only.

4. Root Cause Analysis

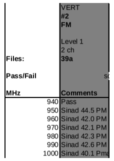


No	Potential Causes	Reasons
1	Tuner circuit vulnerable to RI	Changes from previous design to include leaded components may have increased some sensitive loop areas.
5.1	Poor shielding for this sample	Checked screw connections on chassis
5.2	Poor grounding for antenna cable	Checked screw mounting antenna cable to chassis - thread was poor and not possible to tighten.

5. Proposed Solution

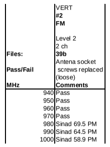
No	Solutions	Type		Effectiveness		
		Temp	Perm	Not	SW	Very
5.2	Fit new screw to ensure design intent contact between antenna screen and chassis	X			X	

BEFORE



AFTER

Pass against 50V/m Level 1 threshold.



6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
5.2.1		Re-test with tight screw	Test labs 0.5 day
5.2.2		Feedback to design and plant	EMC apps 0.5 days

7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?		X	
2. Any consequences to other products/processes?	X		Always ensure that correctly built units submitted for test

8. What

No	Lessons Learnt
1	Poor grounding at antenna connector made unit more vulnerable to Radiated Immunity.
2	Process for supplying units for test needs to ensure quality of build etc.

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Design Rule 1 All cable shield should have (good), preferably 360degree connection to chassis					X		
Recommendation 2 Pre-test check -list to ensure checks that all screws etc. tightened to correct torque etc.							X
3							

10. Now What

DR / Rec	Activity
DR1	Mechanical Detail Design (27)
Rec2	Part and Drawing alignment (32)

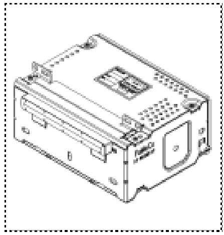
Figure 6.13 A3LAMDA Report 5 documented during RI Problem Solving in Project 4

1. Team: MS **Author:** MS **Date:** 02/05/2012

Title: USB Mode Emissions **A3 Report No:** A3R6

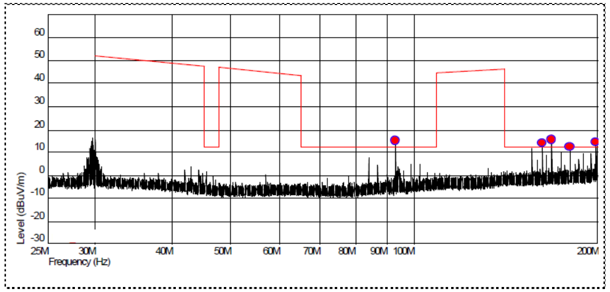
2. Background

Product Type	Audio
Product Name	AudioG
Product Code	XXP8
Software No.	XXS8
PCB No.	XXPCB8
Serial No	XX8
Customer Spec	A
Other Information:	

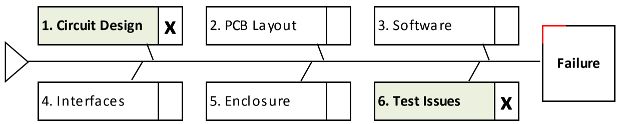


3. Current Condition

Test Request No	XTRQ8	Funct Status	I
Test Report No	XTRP8	Funct Perform Class	A
Test Type	RE XX	Occurrence	2
Other Information: Emissions exceede in USB mode in FM and VHF bands and at 201MHz			



4. Root Cause Analysis

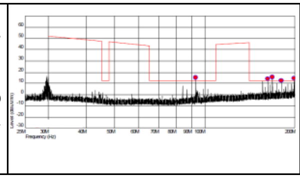


No	Potential Causes	Reasons
1	Circuit design/layout	Unlikely, as changes mode in Parrott module software and hardware not expected to affect USB.
6.1	Test set-up	Checks made that same load filter used on USB memory stick. New back-back connector used for USB cable. Connector has poor shield continuity. Other test kit the same.
6.2	Test set-up - USB box laid on ground plane rather than on insulator	Gives different coupling between stick and GND plane.

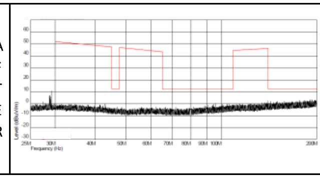
5. Proposed Solution

No	Solutions	Type: Temp	Type: Perm	Effectiveness: Not	Effectiveness: SW	Effectiveness: Very
6.2	Improve shield continuity on USB back-back connector (Copper Tape)		X			X

BEFORE



AFTER



6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
6.2.1		Re-test with corrected connector	Test lab 1 day

7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?		X	
2. Any consequences to other products/processes?		X	

8. What

No	Lessons Learnt
1	Support equipment is key to measured reults.
2	Problem introduced because support kit changed from first test phase.
3	Support kit should be validated before use (unfortunatley, in this case would need to have done an RE test to check the support kit !)

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation 1							
Check that support kit the same before testing, or re-validate any new/changed kit						X	
2							
3							

10. Now What

DR / Rec	Activity
Rec1	Specify, Develop and Accept Test Equipment (56)
	Test and Report (58)
	Final Review of Test Plans and Reports (59)

Figure 6.14 A3LAMDA Report 6 documented during RE Problem Solving in Project 5

The task of dynamically capture EMC knowledge during problem solving using A3LAMDA had a duration of five months and obtained the following results:

- 6 A3LAMDA reports completed
- 9 recommendations and 1 design rule captured
- 15 declaration of P_{nd} knowledge needed attributes

The fact that only one captured knowledge was declared as a design rule highlights the expected challenge of explicit knowledge creation in the, to some extent, unpredictable EMC domain.

The number of knowledge captured per A3LAMDA report varies. A3LAMDA reports number 2 (Figure 6.10), 4 (Figure 6.12) and 5 (Figure 6.13) resulted in one knowledge capture entry. A3LAMDA report number 1 (Figure 6.9) and number 5 (Figure 6.13) resulted in two knowledge capture entries. In A3LAMDA report number 3 (Figure 6.11) on the other hand, authors completed all three entry cells for knowledge capture.

Table 6.3 illustrates the identified design issues from task 1.4 in Section 6.2.1, in relation to the dynamically captured knowledge. Circuit design and test issues were declared three times, whereby software and enclosure conceded one relation to the dynamically captured knowledge.

Table 6.3 Design Issues in relation to Dynamically Captured Knowledge

Design Issue	**Related to Dynamically Captured Knowledge**
Circuit Design	3
Printed Circuit Board (PCB) Layout	0
Software	1
Interfaces	0
Enclosure	1
Test Issues	3
Other	2

Design issues of PCB layout and interface have not been selected by the problem solving team in the scope of the dynamic knowledge capture activities. In A3LAMDA reports number2 (Figure 6.10) and 5 (Figure 6.13), knowledge captured was declared as ‘other’ design issue. If in time the selection of ‘other’ design issues increases, new design issues are apparent and require further investigation to be updated in the standard A3LAMDA template in company A.

6.2.3 Knowledge Representation: Stage 3 of the LeanKLC in Case Study 1

Task 3.1 Define Key EMC Knowledge Attributes

Knowledge created P_{cr}: originates from the function of the A3LAMDA authors, this being electrical engineering, although within a particular phase of the product development process in which the failure occurred.

Type of Knowledge:

- Knowledge related to design issues of circuit design, PCB layout, software, interface and enclosure equal to product knowledge
- Knowledge related to design issue of test issues equal to process knowledge
- Knowledge declared as recommendation equal to tacit knowledge
- Knowledge declared as design rule equal to explicit knowledge

Knowledge needed P_{nd}: is declared for every dynamically captured knowledge in element number10 (now what) in the A3LAMDA report.

Value over Time: is declared by giving feedback rating of usefulness via a Likert scale on the provided knowledge at a particular time and place in the product development process, as will be demonstrated in Section 6.2.6.

Task 3.2 Graphically Represent EMC Knowledge Provision during New Product Development

This task visually displays the right time and place of the right knowledge provision during a new product development project. Accordingly, the definition of unit vectors $\overrightarrow{e_x}$, $\overrightarrow{e_y}$ and $\overrightarrow{e_z}$ is based on the existing product development process in company A and illustrated in Figure 6.15.

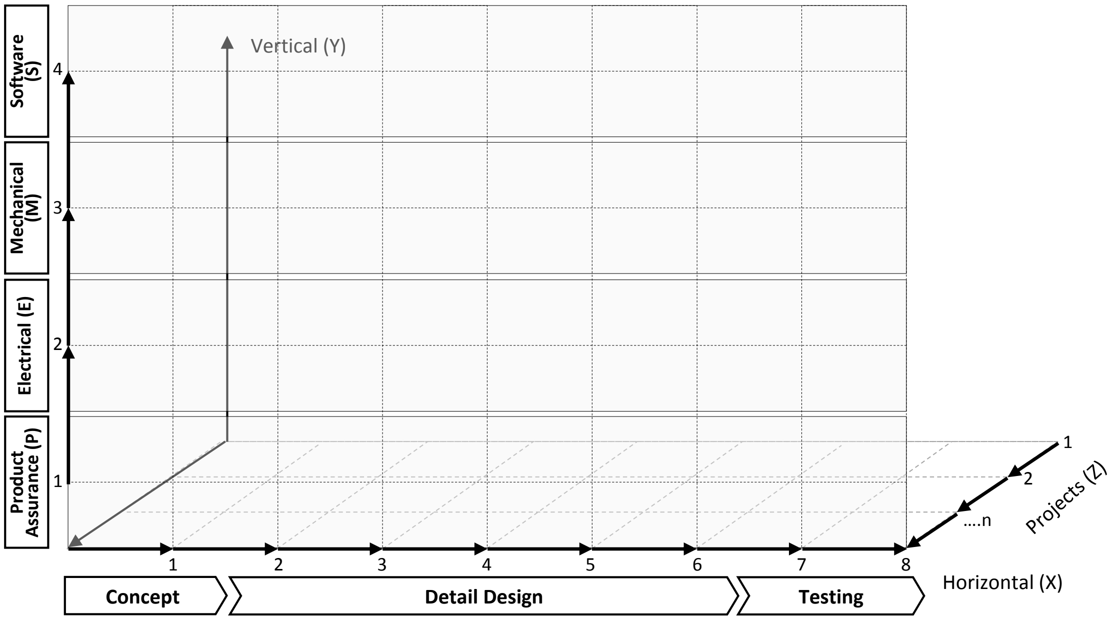


Figure 6.15 Definition of Unit Vectors for Product Development Process in Company A

Horizontal unit vector $\overrightarrow{e_x}$: is equal to one for each sequential activity within the product development phases of concept, detail design and testing. For example, activities 2, 3, 4, 5 and 6 are part of the detail design phase.

Vertical unit vector $\overrightarrow{e_y}$: is equal to one for each product development function, these being product assurance, electrical, mechanical and software.

Previous projects unit vector $\overrightarrow{e_z}$: is equal to one for each project accomplished.

Given the above, Table 6.4 contains the declared and unique coordinates for the P_{cr} and P_{nd} attributes from the six A3LAMDA reports completed in the LeanKLC stage of dynamic knowledge capture. Consequently, the knowledge provision vectors for every knowledge needed in a future project are determined as a vector between two points $\overrightarrow{P_{cr}P_{nd}}$. Hence, five projects comprised the scope of A3LAMDA report completion for dynamic knowledge capturing; the next future project is equal to project number six. Therefore, every knowledge needed coordinates P_{nd} receive number six as project z_{nd} coordinate (x_{nd}; y_{nd};6) for graphical representation of knowledge provision.

Table 6.4 Knowledge Provision Vector Definition at Company A

A3LAMDA Report no.	Activity (x_{cr})	Function (y_{cr})	Project (z_{cr})	Knowledge Created P_{cr} (x_{cr}; y_{cr}; z_{cr})	Design Rule / Recommendation	Knowledge Needed P_{nd} (x_{nd}; y_{nd}; z_{nd})	Knowledge Provision Vector $\overrightarrow{P_{cr}P_{nd}}$
1	7	2	1	(7;2;1)	Rec1.1	(2;2;6)	$\vec{a} = \begin{pmatrix} 2-7 \\ 2-2 \\ 6-1 \end{pmatrix} = \begin{pmatrix} -5 \\ 0 \\ 5 \end{pmatrix}$
					Rec1.2	(3;1;6)	$\vec{b} = \begin{pmatrix} 3-7 \\ 1-2 \\ 6-1 \end{pmatrix} = \begin{pmatrix} -4 \\ -1 \\ 5 \end{pmatrix}$
2	3	2	2	(3;2;2)	Rec2.1	(7;2;6)	$\vec{c} = \begin{pmatrix} 7-3 \\ 2-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} 4 \\ 0 \\ 4 \end{pmatrix}$
						(3;1;6)	$\vec{d} = \begin{pmatrix} 3-3 \\ 1-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 4 \end{pmatrix}$
						(7;1;6)	$\vec{f} = \begin{pmatrix} 7-3 \\ 1-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} 4 \\ -1 \\ 4 \end{pmatrix}$
3	6	2	2	(6;2;2)	Rec3.1	(5;2;6)	$\vec{g} = \begin{pmatrix} 5-6 \\ 2-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} -1 \\ 0 \\ 4 \end{pmatrix}$
					Rec3.2	(2;2;6)	$\vec{h} = \begin{pmatrix} 2-6 \\ 2-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} -4 \\ 0 \\ 4 \end{pmatrix}$
					Rec3.3	(4;4;6)	$\vec{r} = \begin{pmatrix} 4-6 \\ 4-2 \\ 6-2 \end{pmatrix} = \begin{pmatrix} -2 \\ 2 \\ 4 \end{pmatrix}$
4	8	2	3	(8;2;3)	Rec4.1	(6;1;6)	$\vec{j} = \begin{pmatrix} 6-8 \\ 1-2 \\ 6-3 \end{pmatrix} = \begin{pmatrix} -2 \\ -1 \\ 3 \end{pmatrix}$
						(4;2;6)	$\vec{k} = \begin{pmatrix} 4-8 \\ 2-2 \\ 6-3 \end{pmatrix} = \begin{pmatrix} -4 \\ 0 \\ 3 \end{pmatrix}$
5	1	2	4	(1;2;4)	DR5.1	(4;3;6)	$\vec{l} = \begin{pmatrix} 4-1 \\ 3-2 \\ 6-4 \end{pmatrix} = \begin{pmatrix} 3 \\ 1 \\ 2 \end{pmatrix}$
					Rec5.2	(6;3;6)	$\vec{m} = \begin{pmatrix} 6-1 \\ 3-2 \\ 6-4 \end{pmatrix} = \begin{pmatrix} 5 \\ 1 \\ 2 \end{pmatrix}$
6	4	2	5	(4;2;5)	Rec6.1	(4;1;6)	$\vec{n} = \begin{pmatrix} 4-4 \\ 1-2 \\ 6-5 \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix}$
						(7;1;6)	$\vec{o} = \begin{pmatrix} 7-4 \\ 1-2 \\ 6-5 \end{pmatrix} = \begin{pmatrix} 3 \\ -1 \\ 1 \end{pmatrix}$
						(8;1;6)	$\vec{p} = \begin{pmatrix} 8-4 \\ 1-2 \\ 6-5 \end{pmatrix} = \begin{pmatrix} 4 \\ -1 \\ 1 \end{pmatrix}$

The resulting 15 knowledge provision vectors are named in alphabetical order from $\vec{a}$ to $\vec{p}$. The following explains the graphical representation of knowledge provision using vectors for particular functions in the product development process of company A, in order to visualise the provision of right knowledge at the right time and place during new project number 6.

Vector Representation of Knowledge Provision during Software and Mechanical Engineering

This section describes the cross-functional knowledge provision to the functions of software and mechanical engineering. For the function of software engineering, engineers declared one recommendation to be needed in activity four during detail design, represented as vector $\vec{r}$ in Figure 6.16. The knowledge was dynamically captured during A3LAMDA report number 3, in which the problem solving team realised the necessity of reviewing software for graceful handling in order to reduce risk of radiated immunity failure.

Vectors $\vec{l}$ and $\vec{m}$ both originate from A3LAMDA report number 5 and both are needed in the mechanical engineering function, as shown in Figure 6.16.

Vector $\vec{l}$ represents the knowledge provision of the design rule in which engineers demand that cables should have 360 degree connection to the chassis in order to enhance radiated immunity.

Vector $\vec{m}$ entails the provision of a recommendation for radiated immunity although related to tightening of screws with correct torque and is needed in activity six during detail design.

Vectors $\vec{l}$ and $\vec{m}$ have both positive values for (X) coordinates meaning that the knowledge was originally created in a preceding activity. Whereby (X) value for vector $\vec{r}$ is negative; hence this knowledge was created during a proceeding activity in the product development process.

Given the above, Figure 6.16 visually displays the key activities in which software and mechanical engineers require knowledge that originates from the electrical engineering function and therefore provides a vital technique to overcome the challenge of over the wall communication.

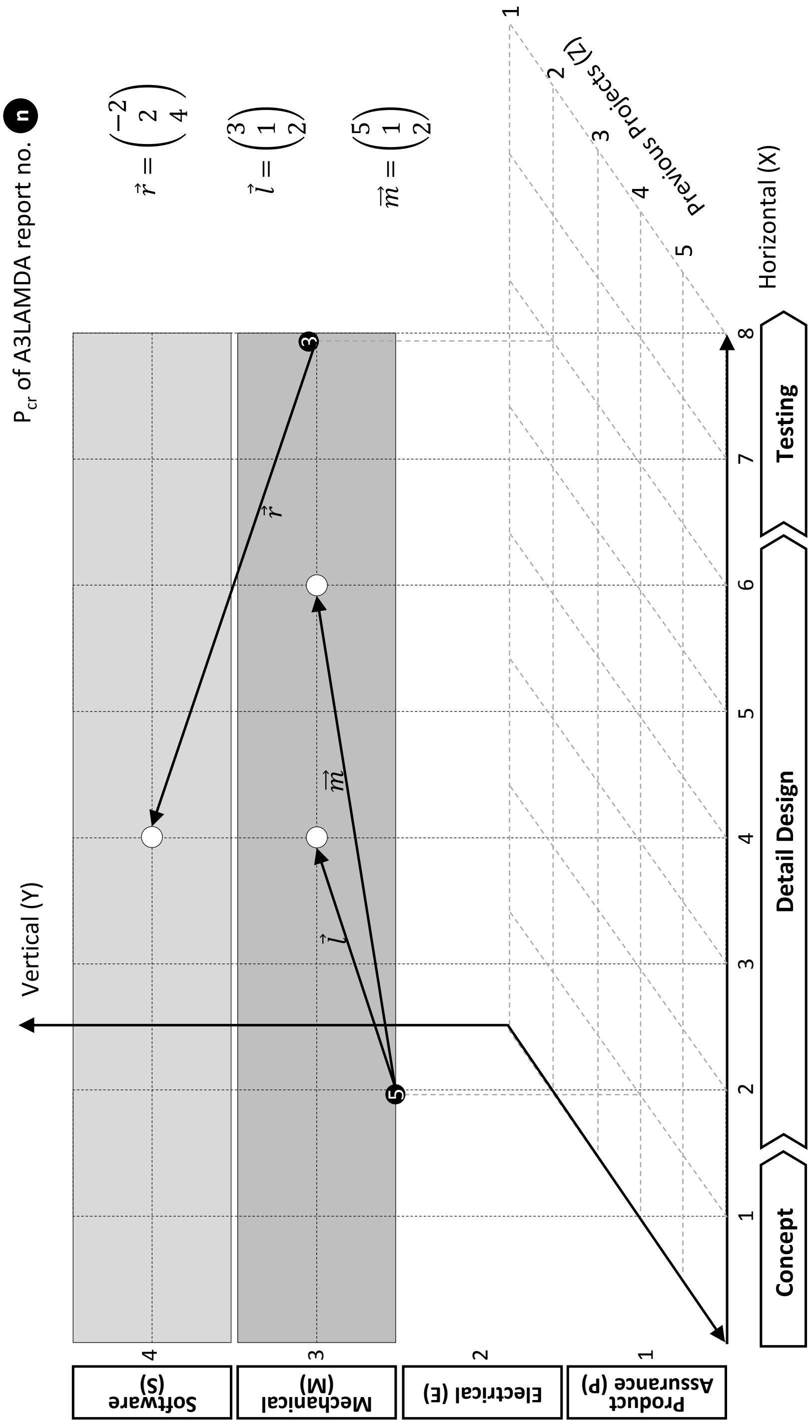


Figure 6.16 Vector Representation of EMC Knowledge Provision during Software and Mechanical Engineering

Vector Representation of Knowledge Provision during Electrical Engineering

As illustrated in Figure 6.17, in case of vector representation of knowledge provision during electrical engineering all vectors have value “0” as (Y) coordinate. This means that all knowledge is created within the same function.

Six knowledge provision vectors are represented to be needed in the electrical engineering function. With regard to horizontal (X) dimension, four vectors, $\vec{a}$, $\vec{g}$, $\vec{h}$ and $\vec{k}$, have negative direction, whereby vector $\vec{c}$ has positive (X) direction. Vector $\vec{a}$ has the biggest magnitude, as defined in case study 1. It originates from A3LAMDA report number 1, which was initiated in activity seven, although its created knowledge is needed in activity two of the product development process.

Two vectors, $\vec{a}$ and $\vec{h}$, have the same knowledge needed P_{nd} activity (schematic design and approval), though being created in two different A3LAMDA reports, one and three. Therefore, knowledge provision in subsequent stage of the LeanKLC was undertaken during this particular activity and is explained in Section 6.2.6.

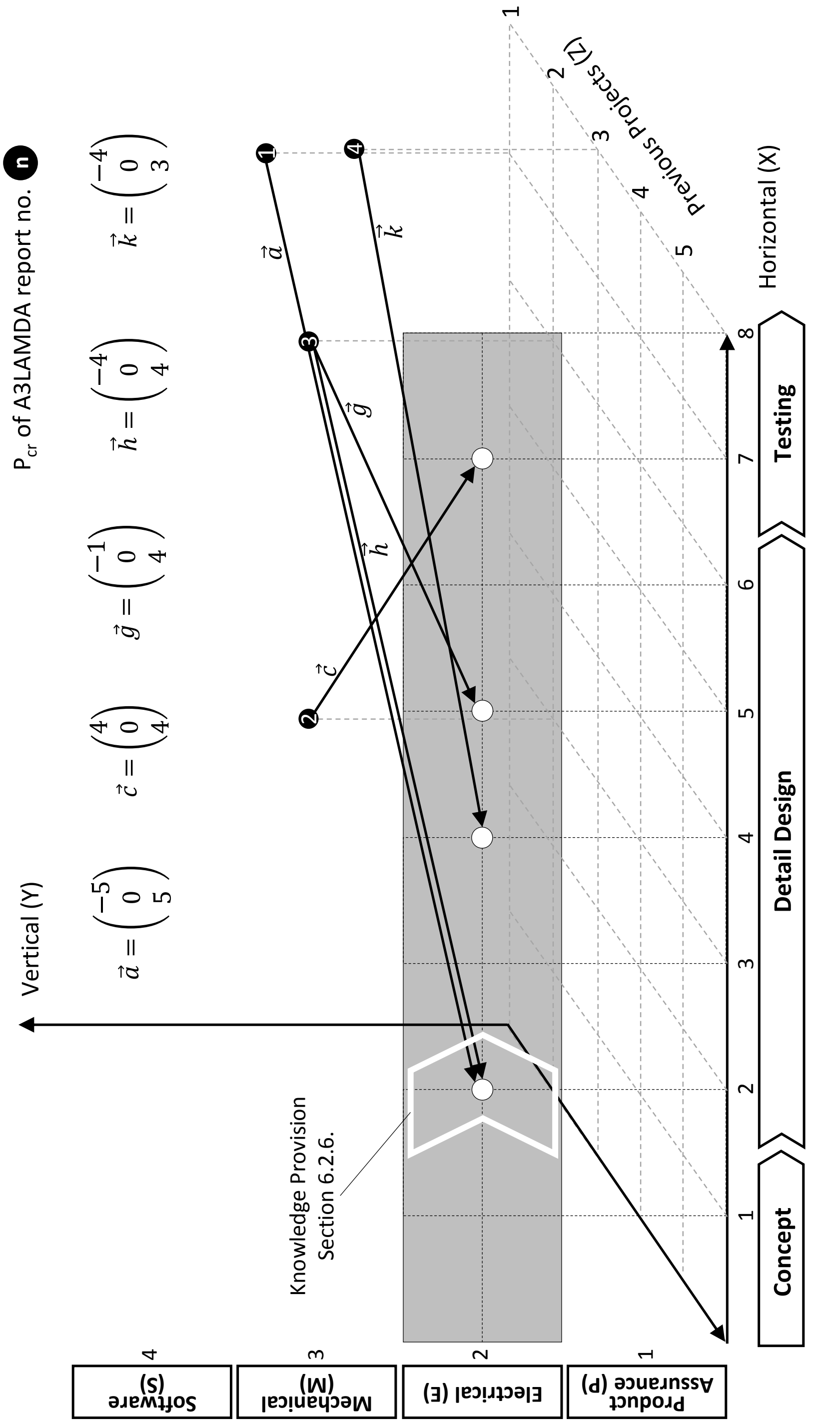


Figure 6.17 Vector Representation of EMC Knowledge Provision during Electrical Engineering

Vector Representation of Knowledge Provision during Product Assurance

Product assurance is the product development function in which problem solving teams declared most of the knowledge needed activities during dynamic knowledge capturing. As illustrated in Figure 6.18, a total of seven knowledge provision vectors are represented, these are $\vec{b}$, $\vec{d}$, $\vec{f}$, $\vec{j}$, $\vec{n}$, $\vec{o}$ and $\vec{p}$.

Vector $\vec{n}$ has the lowest magnitude of all vectors represented during case study 1. It was created in project five during electrical engineering.

Vector $\vec{j}$ represents a condition in which knowledge was created at a late stage of testing, but which however is needed at the early stage in future product development projects.

Vectors $\vec{n}$, $\vec{o}$ and $\vec{p}$ originate from A3LAMDA report number 6, entailing a recommendation that emphasises on pre check support kit before any new validation. This recommendation was declared as needed in three activities in X dimension, these being activities four, six and eight during product assurance.

Two knowledge provision vectors each are represented for activities three ($\vec{b}$ and $\vec{d}$) and seven ($\vec{f}$ and $\vec{o}$) in the product assurance function. The knowledge provision for activity three during product assurance, vectors $\vec{b}$ and $\vec{d}$, is subject to knowledge provision as part of the case study validation and explained in Section 6.2.6.

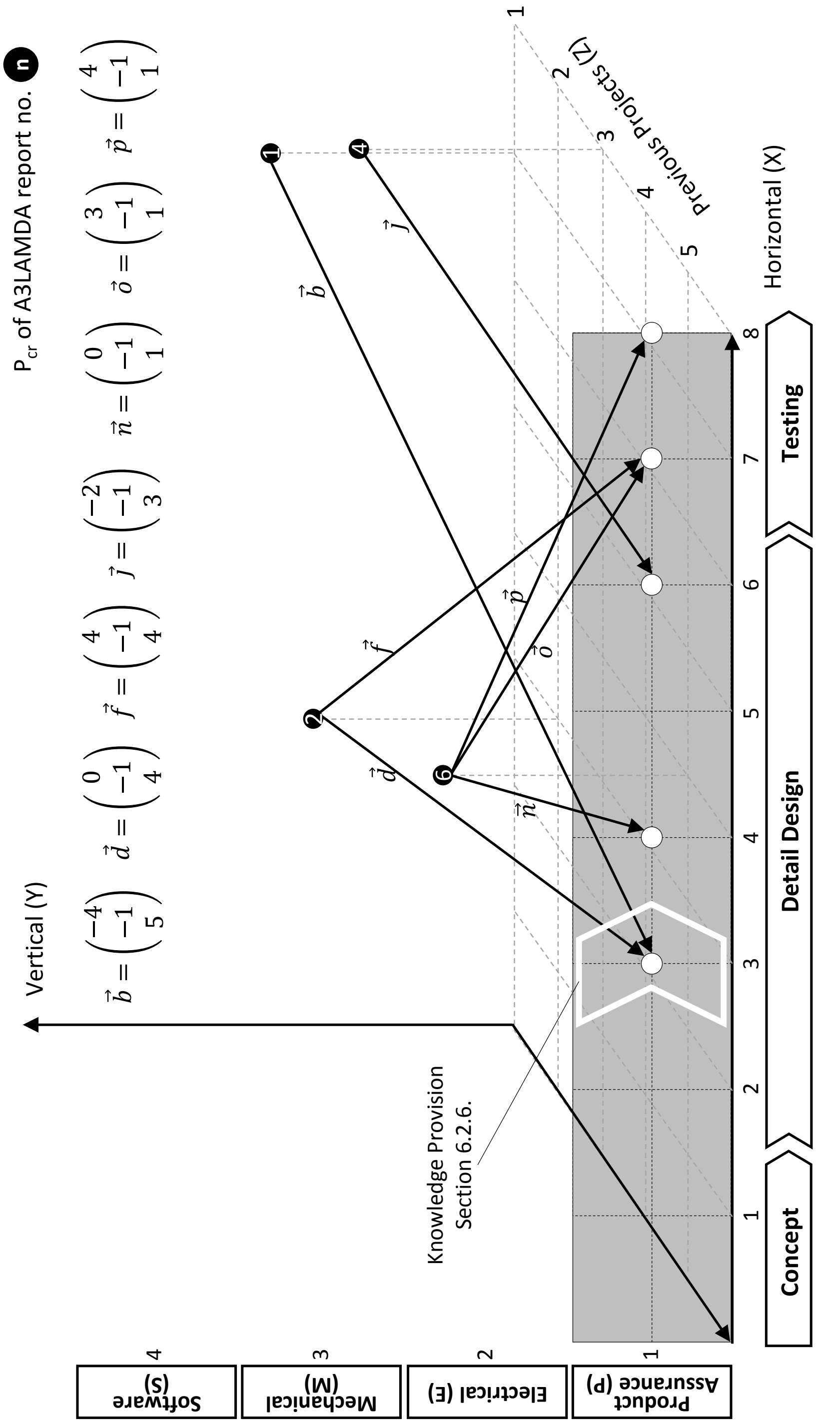


Figure 6.18 Vector Representation of EMC Knowledge Provision during Product Assurance

6.2.4 Knowledge Sharing: Stage 4 of the LeanKLC in Case Study 1

Task 4.1 Centralise EMC Knowledge

Centralised knowledge as envisioned in the To-Be knowledge environment is illustrated in Figure 6.4-b. This however, requires the integration of such EMC knowledge in a structured knowledge base and will be explained in Section 6.2.5.

Task 4.2 Facilitate EMC Knowledge Sharing

Facilitating knowledge sharing comprises the formal and structured continuous improvement initiative for problem solving using A3LAMDA in a multidisciplinary team.

Task 4.3 Share EMC Knowledge through Visualisation

In particular during EMC testing, electrical engineers expressed cases of recurring issues after solving a problem. Therefore, knowledge sharing through visualisation is established using the enhanced element number 5 (proposed solution) and element number7 (prevent recurrence) in the A3LAMDA template, as illustrated in Figure 6.7.

During the completion of six A3LAMDA reports, the problem solving team proposed a total of 12 solutions, although 10 have been verified, as shown in Table 6.5.

Table 6.5 Knowledge Sharing of Proposed and Implemented Design Solutions using A3LAMDA Report

Total Number of Proposed Design Solutions	**12**
Number of verified Design Solutions	**10**
Not Effective	4
Somewhat Effective	3
Very Effective	3
Number of implemented Design Solutions	**6**
Not Effective	0
Somewhat Effective	3
Very Effective	3
Temporary	2
Permanent	4

Four of the verified proposed design solutions were rated as not effective, meaning that creating knowledge as a result of problem solving requires the generation of multiple proposed design solutions. Three implemented design solutions have been rated somewhat effective and three have been rated very effective, as shown in Table 6.5. Hence, problem solving teams generated design solution until at least a somewhat effective design solution was achieved. On the other hand, two implemented design solutions have been rated as temporary solutions, whereby the remaining four have been rated as permanent solutions. As such, element number 5 (proposed solution) in the enhanced A3LAMDA template prompts attention for engineers to participate in the problem solving activity and share knowledge to generate effective and permanent design solutions.

Element number 7 (prevent recurrence) in the A3LAMDA on the other hand, outlines those implemented design solutions that affect other EMC tests, products or processes and therefore triggers immediate knowledge sharing to prevent recurrence.

Table 6.6 Knowledge Sharing to prevent Recurrence using A3LAMDA Report

Total Amount of Implemented Design Solutions	**6**
Does the solution impact other EMC tests?	
YES	2
NO	4
Any consequences to other products/processes?	
YES	2
NO	4

As shown in Table 6.6, two implemented solutions resulting from A3LAMDA reports number 1 and 3 affected other EMC tests. Also, two implemented design solutions resulting from A3LAMDA reports number 4 and 5 affected other products or processes. This indicates that the developed concept of enhancing knowledge sharing in the A3LAMDA template, as described in 5.5.4.3, is apparent in order to formally share knowledge during problem solving.

6.2.5 Knowledge Integration: Stage 5 of the LeanKLC in Case Study 1

Task 5.1 Gather Functional Requirements for LeanKLC application in Company A

Knowledge integration started with the gathering of functional requirements at company A, the results of which are included in Section 4.2. In particular, company A expressed a need for a mechanism that prioritises knowledge, which was addressed during this research by developing a method for knowledge maintenance as proposed in Appendix C.

Task 5.2 Adapt a System Architecture for LeanKLC application in Company A

The adaption of a system architecture in case study 1 is represented in different stages of the LeanKLC. Figure 6.8 illustrates the system architecture as part of dynamic knowledge capturing. Figure 6.20 and Figure 6.22 on the other hand display different scenarios in the system architecture during knowledge provision.

Task 5.3 Integrate EMC Knowledge in a Centralised Knowledge Base

The task of integrating knowledge in a centralised knowledge base was accomplished as illustrated in Figure 6.19. This required the definition of additional information as related to EMC testing, these being:

- software number
- printed circuit board number
- serial number
- functional class
- functional status.

Each knowledge base entry is interlinked with corresponding entry cells in the A3LAMDA templates meaning that data is populated while the A3LAMDA authors complete a report in a dynamic manner. Consequently, Figure 6.19 illustrates the knowledge base resulting from dynamic knowledge capture from the six completed A3LAMDA reports.

EMC Knowledge Base

A3LAMDA Report No.	Date	Product Type	Product Name	Product Code	Software No.	PCB No.	Serial No.	Test Request No.	Test Type	Functional Class	Functional Status	Occurrence	A3LAMDA Source	Eelements Completed	Not Effective	Somewhat Effective	Very Effective	Temporary Solution	Permanent Solution	Affects Other EMC		Affects Other Products		Design Rule or Recommendation	Knowledge Capture	Related Design Issue	Knowledge Needed Pnd
		Failure Documentation											Problem Solving		Implemented Solution									Knowledge Capture - Reflection			
1	01/12/2011	Audio	AudioB	XXP3	XXS3	XXPCB3	XX3	XTRQ3	RE XX	A	II	1	A3R1	9		X			X	X			X	Rec1	Class-D Output Low Pass filter should have low enough cut-off to reduce amplitude of switching frequency and harmonics.	Circuit Design	Schematic Design and Approval (41) 0 0
																								Rec2	Testing needs to ensure that all outputs fully exercised.	Test Issues	elop Hardware Test Plan, ADVP, DVP (62) 0 0
2	03/01/2012	Audio	AudioD	XXP4	XXS4	XXPCB4	XX4	XTRQ4	CI XX	A	II	1	A3R2	10			X		X		X		X	Rec1	EMC test plan clearly defines recovery sequence after immnunity events.	Other	Support EMC Design Validation (53) elop Hardware Test Plan, ADVP, DVP (62) Test and Report (58)
3	27/02/2012	Audio	AudioD	XXP4	XXS4	XXPCB4	XX4	XTRQ5	RI XX	A	II	2	A3R3	10			X	X		X			X	Rec1	Specify in EMC test plan whether it is necessary to apply field for longer than the 2s minimum	Test Issues	Develop end of line test parameters (54) 0 0
																								Rec2	Review SPI interface for vulnerability to radiated fields.	Circuit Design	Schematic Design and Approval (41) 0 0
																								Rec3	Review software for graceful handling of eroors on internal interfaces	Software	Software Detail Design (104) 0 0
4	03/03/2012	Instrument Cluster	ClusterB	XXP6	XXS6	XXPCB6	XX6	XTRQ6	RE XX	A	I	2	A3R4	10		X			X		X	X		Rec1	The pre-DV test must be correctly and fully performed before validation.	Circuit Design	Test Go/NoGo Decision (85) Develop Verification Test Plans (49) 0
5	23/04/2012	Audio	AudioF	XXP7	XXS7	XXPCB7	XX7	XTRP7	RI XX	A	II	3	A3R5	10		X		X			X	X		DR1	All cable shield should have (good), preferably 360degree connection to chassis	Enclosure	Mechanical Detail Design (27) 0 0
																								Rec2	Pre-test check -list to ensure checks that all screws etc. tightened to correct torque etc.	Other	Part and Drawing alignment (32) 0 0
6	02/05/2012	Audio	AudioG	XXP8	XXS8	XXPCB8	XX8	XTRQ8	RE XX	A	I	2	A3R6	10			X		X		X		X	Rec1	Check that support kit the same before testing, or re-validate any new/changed kit	Test Issues	Develop and Accept Test Equipment (56) Test and Report (58) al Review of Test Plans and Reports (59)

Figure 6.19 EMC Knowledge Base resulting from six completed A3LAMDA Reports

6.2.6 Knowledge Use and Provision: Stage 6 of the LeanKLC in Case Study 1

Task 6.2 Establish a Mechanism that Supports EMC Knowledge Provision

The declaration of knowledge needed attributes P_{nd} in element number 10 (now what) in the A3LAMDA report supports future knowledge provision by relating knowledge to a particular activity in the product development process. This resulted in a total of 15 P_{nd} declarations during LeanKLC application in case study 1. Whilst problem solving was initiated in the electrical engineering function, 10 P_{nd} attributes indicated that created knowledge is needed in other functions, these being:

- one knowledge captured was declared needed in software engineering
- two knowledge captured were declared needed in mechanical engineering
- seven knowledge captured were declared needed in product assurance.

Hence, the potential of the three dimensions of knowledge management in product development unleashes the potential to use knowledge beyond a single application but moreover formally establish a mechanism that declares future provision of dynamically captured knowledge in a cross-functional product development environment.

Task 6.3 Provide Useful EMC Knowledge at the Right Time and Place

Knowledge was provided to PD engineers during the development project of a new audio product in two different activities, these being:

1. Audio schematic design review in the electrical engineering function
2. Development of hardware test plan in the product assurance function.

Previously, these particular instances of knowledge provision have been graphically represented using vectors in Section 6.2.3, Figure 6.17 and Figure 6.18.

EMC knowledge provision during schematic design review

Schematic design review is a formal stage gate review during detail design, in which the EMC application engineer examines and discusses the schematics as put forward by the designers for potential risks that could affect the EMC test performance, such as grounding, power supply, high-speed signals, clock rates and filtering.

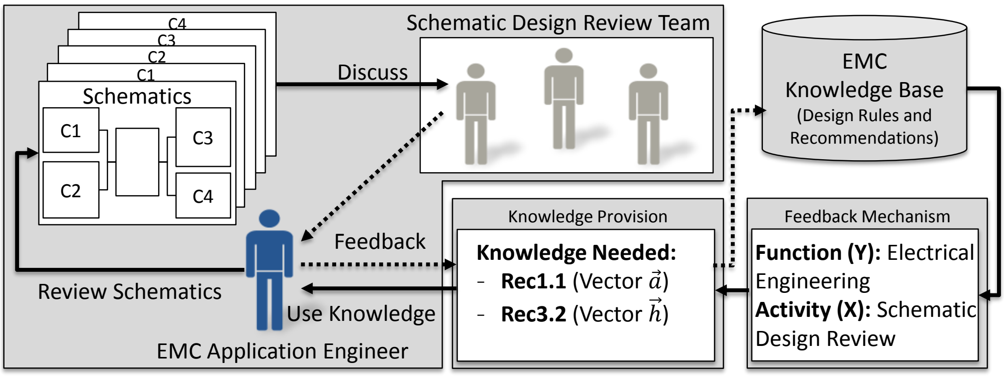
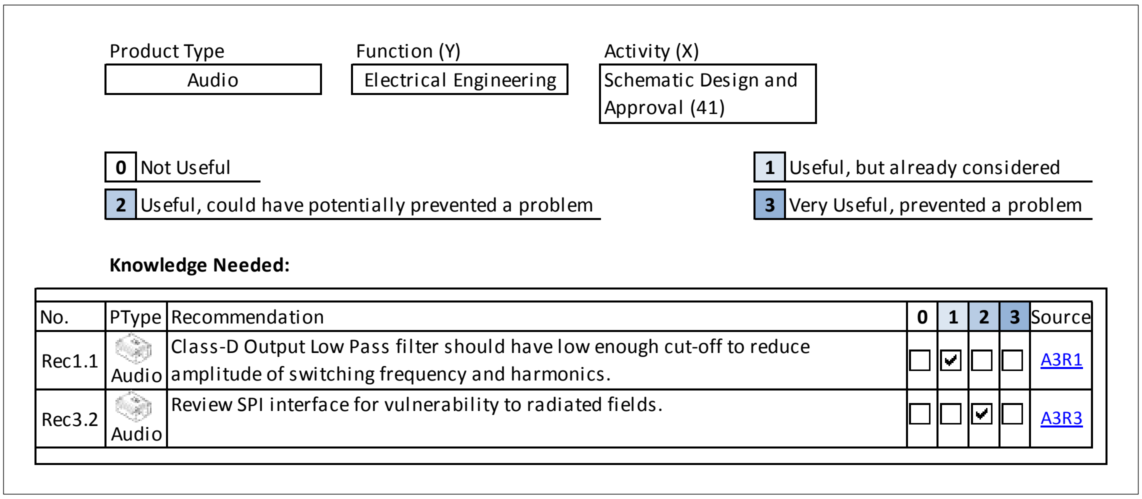


Figure 6.20 EMC Knowledge Provision Scenario during Schematic Design Review

During LeanKLC application on the other hand, knowledge was provided beforehand in a schematic design review activity to the EMC application engineer, as shown in Figure 6.20. Hence the EMC application engineer uses the knowledge, ranks the feedback and discusses it during the schematic design review meeting. During dynamic knowledge capturing two recommendations, Rec1.1 and Rec3.2, have been declared as needed during the schematic design review.



Product Type: Audio

Function (Y): Electrical Engineering

Activity (X): Schematic Design and Approval (41)

0 Not Useful

1 Useful, but already considered

2 Useful, could have potentially prevented a problem

3 Very Useful, prevented a problem

Knowledge Needed:

No.	PType	Recommendation	0	1	2	3	Source
Rec1.1	Audio	Class-D Output Low Pass filter should have low enough cut-off to reduce amplitude of switching frequency and harmonics.	☐	☑	☐	☐	A3R1
Rec3.2	Audio	Review SPI interface for vulnerability to radiated fields.	☐	☐	☑	☐	A3R3

Figure 6.21 Form of EMC Knowledge Provision during Schematic Design Review

The EMC knowledge as provided is shown in Figure 6.21 and rated as follows:

- Rec1.1 (vector $\vec{a}$) was rated '1', meaning that it is useful but already considered in the schematics. Nevertheless, it is vital to be provided at this review; hence engineers with less experience would potentially not have considered this knowledge.
- Rec3.2 (vector $\vec{h}$) was rated '2', useful could have potentially prevented a problem. Although Rec3.2 resulted from a problem solving activity where no

permanent solution was found, engineers concluded awareness to potential risks after looking back to the source of knowledge, A3LAMDA report number3 (illustrated as A3R3 in Figure 6.21).

Therefore, it is important to have a library of A3LAMDA reports available for the engineers to back track the origin, sequence and logic of problem solving activities related to the knowledge being provided.

EMC knowledge provision during hardware test plan development

The second instance of knowledge provision was undertaken as illustrated in Figure 6.22. In this case, a product assurance engineer writes the EMC test plan specifying parameters, procedures as well as arrangement of equipment according to customer requirements. Hence, the test plan is also a communication method with the test lab.

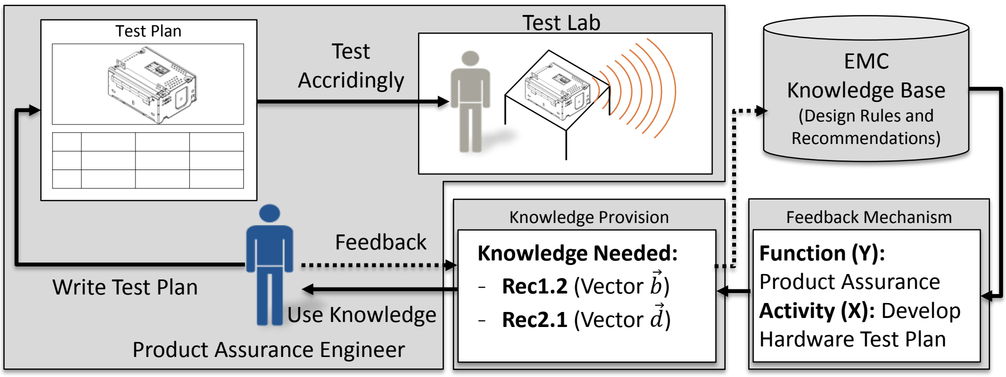


Figure 6.22 EMC Knowledge Provision Scenario during Development of Hardware Test Plan

As opposed to the first instance of knowledge provision, it is not a stage gate review but an activity that the product assurance engineer accomplishes individually. Moreover, the product assurance engineer was new to the job and therefore relying on sufficient knowledge. For this particular activity two recommendations, Rec1.2 and Rec2.1, have been declared as needed.

The EMC knowledge as provided during development of hardware test plan as shown in Figure 6.23 and rated as follows:

- Rec1.2 (vector $\vec{b}$) was rated ‘1’, useful but already considered, as it is included in the existing document template of the hardware test plan.
- Rec2.1 (vector $\vec{d}$) was rated ‘3’, very useful prevented a problem. In fact the current project is a next generation from which Rec2.1 originates (A3LAMDA report number2). The product assurance engineer was not part of the problem

solving activity and therefore not aware of the recommendation to define recovery sequence on immunity related tests.

Product Type	Function (Y)	Activity (X)
Audio	Product Assurance	Develop Hardware Test Plan (62)

0 Not Useful

1 Useful, but already considered

2 Useful, could have potentially prevented a problem

3 Very Useful, prevented a problem

Knowledge Needed:

No.	PType	Recommendation	0	1	2	3	Source
Rec1.2	Audio	Testing needs to ensure that all outputs fully exercised.	☐	☑	☐	☐	A3R1
Rec2.1	Audio	EMC test plan clearly defines recovery sequence after immnunity events.	☐	☐	☐	☑	A3R2

Figure 6.23 Form of EMC Knowledge Provision during Development of Hardware Test Plan

Consequently, the product assurance engineer updated the document template of the test plan in order to ensure that Rec2.1 is part of the standard procedure. This section presented the final stage of the LeanKLC, namely knowledge use and provision, and therefore completes a closed loop industrial application of the LeanKLC in case study 1.

In summary, the LeanKLC, was applied in company A to provide an enhanced continuous improvement process via solving the EMC design problem by dynamically capturing the knowledge resulting from solving the problem. Moreover, the LeanKLC is applied to develop the knowledge environment based on the knowledge created as a result of solving EMC design problems. The next section presents the second LeanKLC case study undertaken in this research.

6.3 Case Study 2: LeanKLC Application in Company B

The application of the LeanKLC in company B has two facets. First, the researcher accomplished the stages and tasks related to the trade-off curves LeanKLC stream as illustrated in Figure 6.24. Second, as part of the LeanPPD project, the researcher guided the development of a knowledge based engineering (KBE) prototype by applying key stages of the LeanKLC.

Lean Knowledge Life Cycle Stages	Tasks accomplished in Case Study Two	Tasks supporting Trade-Off Stream
1. Knowledge Identification	1.1 Increase Awareness in LeanKLC Management to Product Development Engineers	
	1.2 Identify useful Joining Knowledge	
	1.5 Identify Decision Criteria to develop Trade-off Curves for Car Seat Structure Concept Design	X
2. Previous Knowledge Capture	2.1 Structure identified Joining Knowledge	
	2.2 Capture identified Previous Joining Knowledge	
	2.3 Capture Trade-Off Knowledge for designing Car Seat Structures during Concept Design	X
3. Knowledge Representation	3.3 Formally Represent Captured Joining Knowledge	
4. Knowledge Sharing	4.1 Centralise captured Joining Knowledge	
	4.3 Share Knowledge through Visualisation in Company B	X
5. Knowledge Integration	5.1 Gather Functional Requirements in Company B	
	5.2 Adapt a System Architecture to Develop a KBE Prototype	
6. Knowledge Use and Provision	6.1 Use Trade-off Knowledge during Set Narrowing Phase when designing Car Seat Structures	X

Figure 6.24 LeanKLC application in Case Study 2 at Company B

Developing and manufacturing car seat structures as a main capability of company B contains the expertise in both product and process related joining domain knowledge. The manufacturing process starts with hydraulic or mechanical presses that form, cut and bend sheet metal components using follow-on or total composite tools, depending on the size, complexity and quantity of the components.

The joining of the components to form a seat structure is accomplished using processes as illustrated in Figure 6.25, according to DIN 8593 standard which include form fit, clinching, riveting, punch riveting, spot welding, projection welding, laser beam welding and adhesive bonding. The appropriate joining process depends on the seat structure design as put forward by the product development department. Finally, seat structures undergo painting process as a fully automated process and packaging before being despatched to the automotive OEM.

In the described manufacturing process product designers and engineers have significant influence because product designs change depending on the joining processes selected and vice versa. For example, a design solution made from components with different material cannot be spot or laser welded. For product designers and engineers the trade-off between manufacturability and customer requirements is largely apparent combined with the necessity of developing a product in a short time.

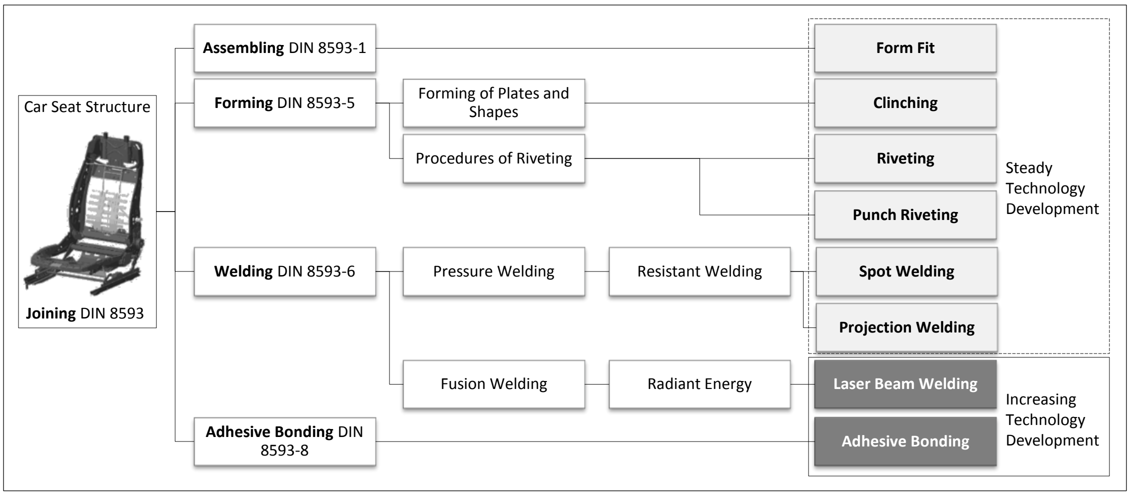


Figure 6.25 Joining Processes according to DIN 8593 Standard (Grote and Antonsson, 2009) identified for Company B

As a result, product designers and engineers tend to use most convenient joining processes, such as form fit, clinching, riveting, punch riveting, spot welding, projection welding. These joining processes, however, are evolving at a slower technology development pace compared to laser beam welding and adhesive bonding, as shown in Figure 6.25 (Grote and Antonsson, 2009).

In reality though, laser beam welding and adhesive bonding are less likely to be chosen by product designers as well as manufacturing managers due to their existing less experience in the related joining process and design. As such, capturing knowledge is equally important for company B to increase knowledge in such domains in order to offer products corresponding to developing technologies. This implies for adhesive bonding in developing and manufacturing hybrid designs by joining two different materials in order to decrease weight or optimising joining welds to profit from laser technology in the form of process diversity and speed, leading to cost savings.

Given the above, the application of the LeanKLC at company B was a consequence of increasing the corporate knowledge within evolving joining processes. Moreover, company B was keen to explore the capturing and visualising of product development knowledge using trade-off curves in the concept development stage. The sequences of LeanKLC stages and tasks applied in company B are explained as follows.

6.3.1 Knowledge Identification: Stage 1 of the LeanKLC in Case Study 2

Task 1.1 Increase Awareness in LeanKLC Management to Product Development Engineers

The use of semi structured questionnaires during the industrial field study (Section 4.3) indicated in particular the challenge of awareness in knowledge management in the product development department in company B. Therefore, focus groups were designed to inform about key principles of knowledge management related topics as well as showing case examples based in the apparent joining knowledge domain.

Table 6.7 Outcomes of Increase Awareness Task in Case Study 2

Task 1.1 Outcome	Detail
Objective	- Apply the novel LeanKLC in order capture joining domain specific knowledge for designing and developing car seat structures - Develop trade-off curves to support knowledge re-use during concept development on given decision criteria
Scope	Conceptual design of car seat structures
Research Duration	18 months
Human Resources	- Seven engineers to participate in the industrial field study to investigate current practice in PD knowledge management - Five engineers to participate in open questionnaire sessions to identify useful knowledge - Two LeanPPD partners to develop a KBE prototype based on the identified and captured knowledge - Three engineers to participate in open questionnaire sessions to define key decision criteria and collect relevant information to develop trade-off curves

The main outcomes with regard to objective, scope, research duration and human resources of the LeanKLC application in case study 2 are illustrated in Table 6.7.

The selection of supportive LeanKLC stages and tasks for the development of the KBE prototype on the other hand was undertaken independently by company B and research partners in the LeanPPD project, without direct involvement of the researcher and shown in Figure 6.26. This shows that the LeanKLC can be adapted independently by third parties in real industrial applications.

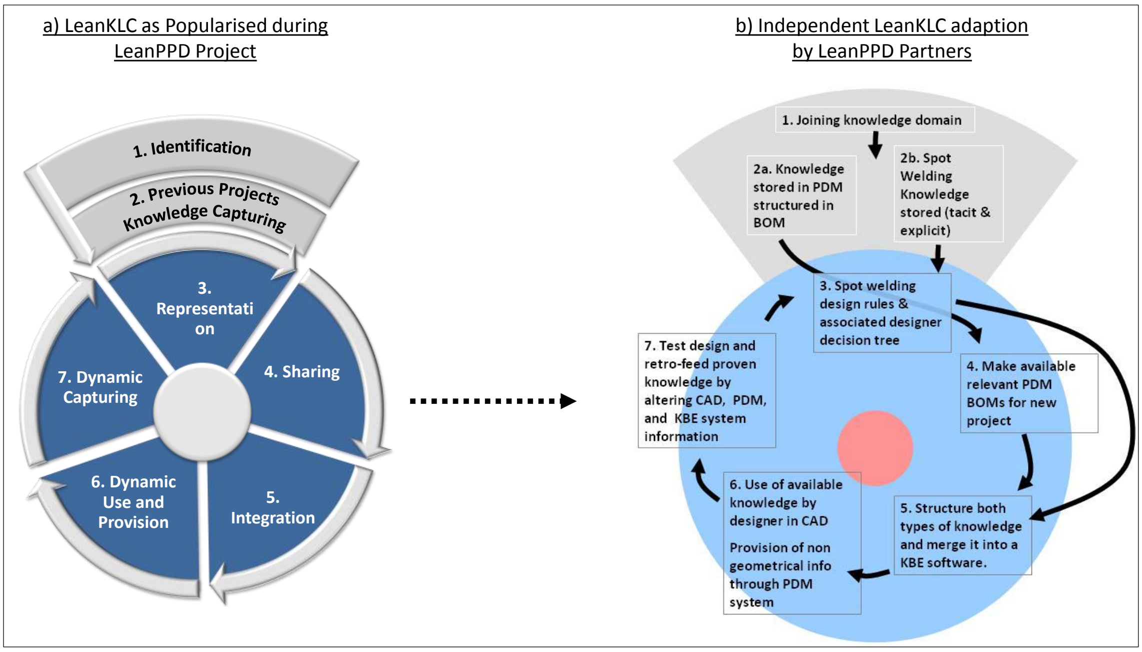


Figure 6.26 Selection of supporting LeanKLC stages and tasks by LeanPPD Partners

Following the key stages of the LeanKLC front loads the consideration of a knowledge environment rather than developing a black box application or closed system KBE prototype. As shown in Figure 6.26-b, these include for example knowledge representation using decision trees to increase usability among engineers as well as centralizing knowledge in a PDM system to facilitate knowledge sharing.

Task 1.2 Identify useful Joining Knowledge

Useful knowledge sources were identified during face to face interviews with product designers and engineers. The key findings on some of the open questions during the identification of useful joining knowledge task 1.2 are summarised in Table 6.8.

Table 6.8 Joining Knowledge Identification Key Findings on selected open Questions

Selected Open Questions	Key Findings
Where does knowledge exist?	- Joining domain specific knowledge is based on design rules as documented in automotive DIN standards
How it was captured before?	- Hence automotive standards exist, there was no formal initiative to capture or mitigate domain specific joining or trade-off knowledge in the past
What knowledge does the product designer or engineer need?	- Joining domain specific design rules to ensure correct parts alignment and manufacturability based on the chosen joining process - Trade-off knowledge that will support decision making in the early concept phase

In the previous section, Figure 6.25 illustrated the particular DIN standards for the relevant joining processes used in company B. Accordingly, engineers have and use published automotive design standards that entail design rules and implications based on one particular joining process.

Task 1.5 Identify Decision Criteria to develop Trade-off Curves for Car Seat Structure Concept Design

During face to face interviews, designers and engineers outlined seven decision criteria apparent during concept design. These then went through pairwise comparison, as illustrated in Table 6.9, in order to evaluate priorities among them.

Table 6.9 Pairwise Comparison Matrix of Decision Criteria during Concept Design of Car Seat Structures

	Durability	Cost	Weight	Surface Finish	Tolerances	Package	Parts Alignment	Priority
Durability	1	1	2	8	9	3	4	***0.287***
Cost	1	1	2	7	6	2	5	***0.261***
Weight	1/2	1/2	1	6	6	1	3	***0.158***
Surface Finish	1/8	1/7	1/6	1	1/3	1/5	1/6	0.025
Tolerances	1/9	1/6	1/6	3	1	1/5	1/7	0.036
Package	1/3	1/2	1	5	5	1	3	***0.142***
Parts Alignment	1/4	1/5	1/3	6	6	1/3	1	0.090

Hence durability, cost, weight and package are perceived by the product development engineers as particularly important during concept deign of car seat structures, trade-off curves will be based on these four decision criteria in case study 2.

During concept design product designers and engineers receive key target values for each decision criteria in the form of customer requirements. Consequently, realizing customer value in the product design is accomplished by fulfilling its given requirements. Certain requirements increase customer value by achieving higher results as required, such as crash performance, of which other exceeds its value when below customer requirements, such as weight, package and cost.

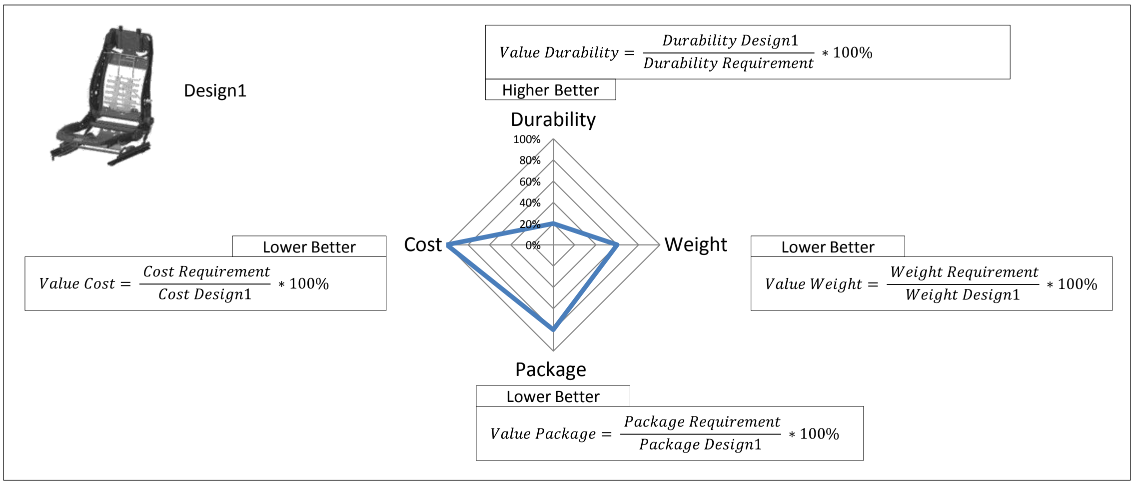
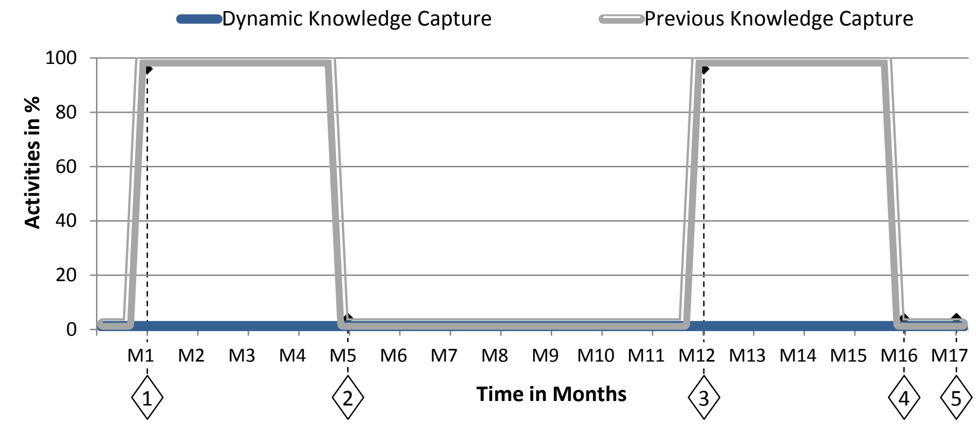


Figure 6.27 Contextualising of Intuitive Value Realisation among the Decision Criteria during Concept Development in Company B

Figure 6.27 illustrates a contextualisation of how product design engineers intuitively balance among the decision criteria in order to realise 100% of customer value realisation in a single design solution. Hence, defining main decision criteria and capturing related trade-off knowledge provides more structure and visual transparency in the decision making process, as will be explained in Section 6.3.6.

6.3.2 Knowledge Capture: Stages 2 and 7 of the LeanKLC in Case Study 2

Previous knowledge capture was undertaken in two main initiatives, as illustrated in Figure 6.28. The first initiative had a duration of four months and comprised the capturing of design rules to mitigate from spot to laser beam welding. This knowledge was later used to develop a KBE prototype, as will be presented in Section 6.3.6.



No.	Knowledge Capture Activities at Milestone during Case Study two
1	Capturing of joining design rules to mitigate from spot to laser welding
2	End of previous knowledge capture activities in first initiative
3	Capturing of joining design rules to mitigate from spot welding to adhesive bonding Capturing of trade-off knowledge based on identified decision criteria
4	End of previous knowledge capture activities in second initiative
5	Company B explores alternative ways of dynamic knowledge capturing

Figure 6.28 Joining Knowledge Capture activities during Case Study 2

The second previous knowledge capture initiative was devoted to capturing design rules to mitigate from spot welding to adhesive bonding as well as the capturing trade-off knowledge based on the identified decision criteria. However, as shown in Figure 6.28, the transition from previous to dynamic knowledge capture was not accomplished in company B within the LeanKLC research duration in case study 2.

Task 2.1 Structure identified Joining Knowledge

The structuring of identified knowledge was undertaken with regard to the identified joining domain, these being spot welding, laser beam welding and adhesive bonding as, shown in Figure 6.29.

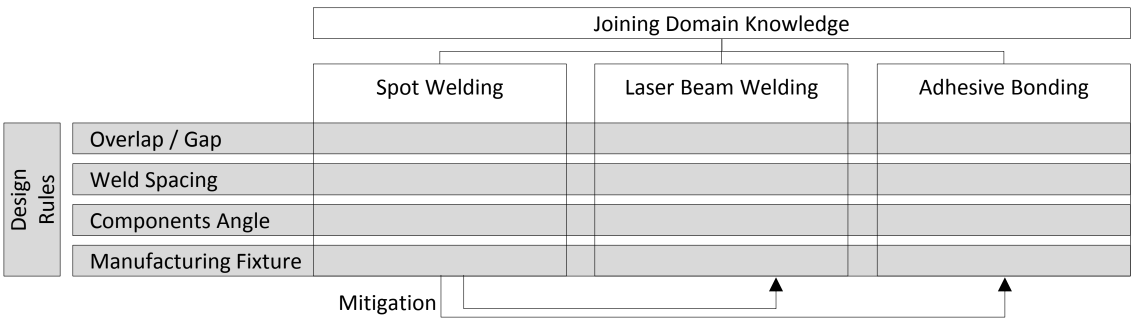


Figure 6.29 Joining Domain Knowledge Structure in Case Study 2 to support Mitigation of Laser Beam Welding and Adhesive Bonding Joining Processes

Design Rules have been further categorized within its major implications to the geometry such as overlap / gap, weld spacing, components angle and manufacturing fixture design in order to realise the mitigation of new joining processes.

Task 2.2 Capture identified Previous Joining Knowledge

Currently, design engineers are most experienced with spot and for this reason laser beam and adhesive knowledge capture has been mitigated accordingly to achieve transition. For example, when designing a component suitable for spot welding the designer adjusts overlap between two sheets based on sheet thickness, weld nugget and spot spacing. In case of laser beam welding on the other hand, the engineer would use a butt joint on two parallel sheets which requires the knowledge to adequately arrange a gap between the sheets depending on sheet thickness, as illustrated in Figure 6.30.

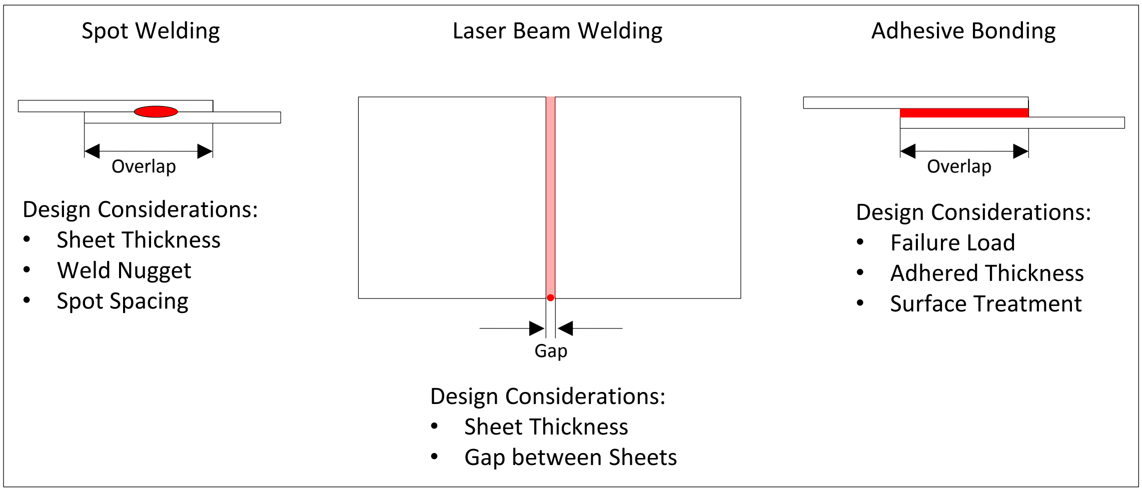
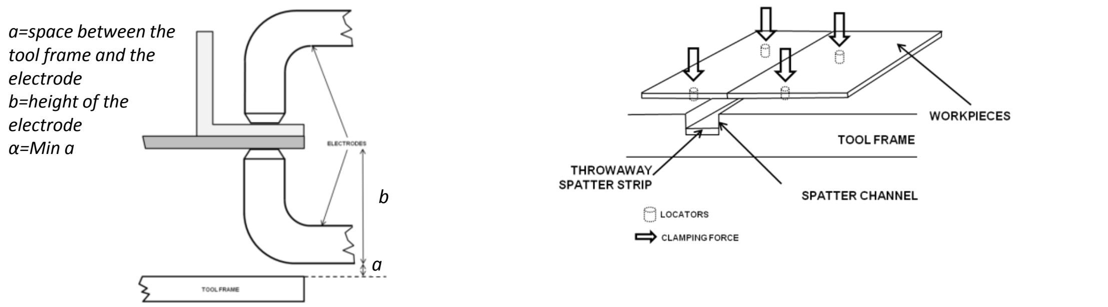


Figure 6.30 Mitigation Example of Design Considerations based on Joining Process Selection

Adhesive bonding overlap is adjusted based on the direction of applied failure load resulting in adequate adhesive thickness as well as requirement for surface treatment. It is evident that engineers have to adapt the design geometry among the different joining methods. Consequently, domain knowledge was captured using design rules and constraints extracted from automotive design standards by formulating If - Then statements.



If (a≤α) then
→ The electrode cannot access to the weld area
→ The electrode cannot open
→ Collisions between the electrode and the tool frame are possible
If (a>α) then
→ the electrode can access safely to the weld area

If (the tool frame has not a spatter channel under the joint)
→ Then spatters and vapours are unable to evacuate causing weld damages and contaminations by back spatter
If (the tool frame has a spatter channel under the joint)
→ then spatters and vapours are able to evacuate

Figure 6.31 Joining Domain Knowledge Capture in Company B using If - Then Statements (Lamacchia, 2010)

Figure 6.31 shows an example of knowledge capture and mitigation for manufacturing fixture design based on spot and laser welding. It displays that spot welding fixture design requires a minimum space for the electrode to access the overlap between the sheets, whereby in case laser beam welding a channel is needed under the weld seam in order to enable spatters and vapours to evacuate.

Task 2.3 Capture Trade-Off Knowledge for designing Car Seat Structures during Concept Design

The capturing of trade-off knowledge comprises the appropriate sheet metal selection during concept design of car seat structures based on the identified decision criteria in Task 1.5 (Section 6.3.1), these being durability, cost, weight and package.

Firstly, material properties based on available fundamental information was extracted from material suppliers as well as from experienced crash parameters embedded in the computer aided engineering system on commonly used sheet metal. As illustrated in Table 6.10, these include density, maximum tensile strength, elongation to break and price. This resulted in the creation of two trade-off curves.

Table 6.10 Data Collection related to Sheet Metal Weight, Durability and Price

	Density in kg/dm^3	Max Tensile Strength in N/mm2	Elongation to Break in %	Price increase on identical dimension in %
Sheet Metal 1 - Aluminium	2.7	270	25	0
Sheet Metal 2 - Steel	7.85	380	26	2
Sheet Metal 3 - Steel	7.85	545	17	12
Sheet Metal 4 - Steel	7.85	580	24	16
Sheet Metal 5 - Steel	7.85	615	12	22
⋮	⋮			
Sheet Metal n				

Trade-off curve one displays the relation among price increase and cost decision criteria, as shown in Figure 6.32. The price increase is based on identical sheet metal dimension in order to have comparable values on sheet metals with different densities; hence the price increases linear to the weight. As a result, engineers obtain the implications regarding cost when choosing material with higher tensile strength on the existing design solution.

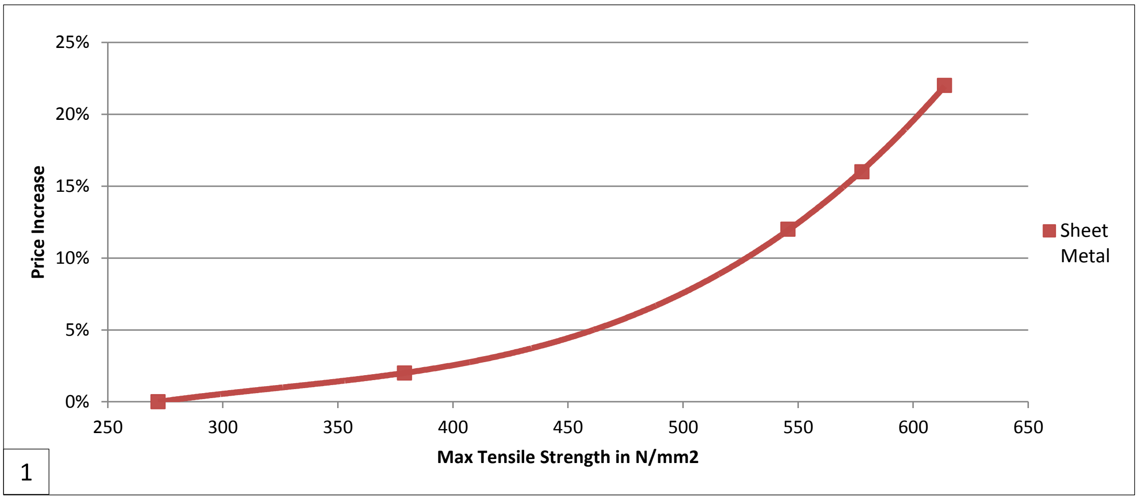


Figure 6.32 Trade-off Curve One - Relation between Decision Criteria of Cost and Durability

Trade-off curve number two, as shown in Figure 6.33, provides additional insights on the durability decision criteria, hence illustrating the implications regarding elongation to break in relation to the tensile strength among the sheet metals.

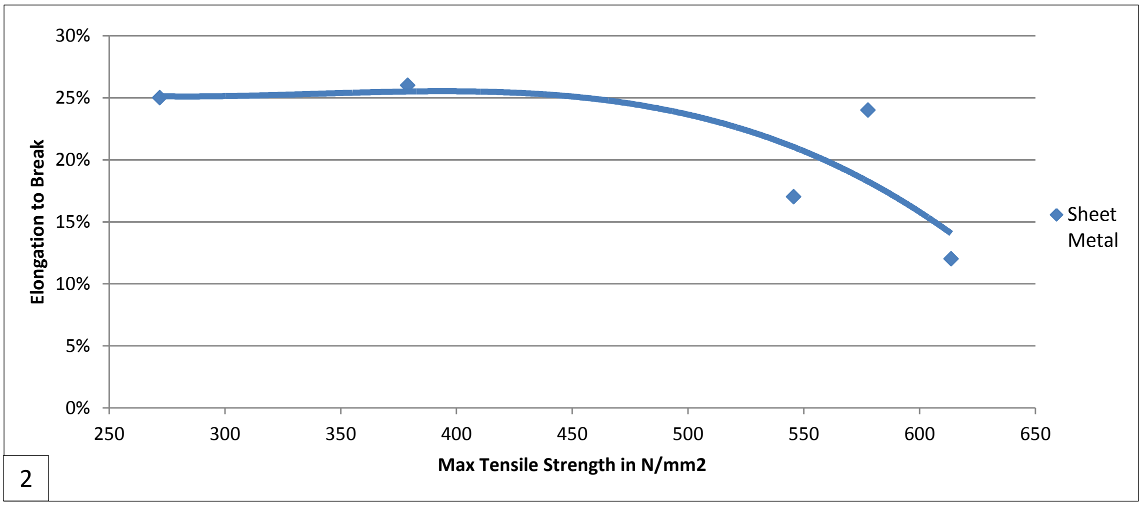


Figure 6.33 Trade-off Curve Two – Based on Durability Decision Criteria

In order to address decision criteria of weight and package, the author captured data based on 15 previous design solutions by providing the ratio of the two decision criteria and sheet metal thickness, as illustrated in Table 6.11.

Table 6.11 Data Collection related to Weight and Package Area of Previous Design Solutions

	Sheet Metal Thickness In mm	Total Design Weight (kg) to Package Area (m^2) Ratio
Design 1	0.5	4.51
Design 2	0.9	2.65
Design 3	0.6	5.33
Design 4	0.6	5.06
Design 5	0.5	4.20
Design 6	0.6	5.05
Design 7	0.6	4.59
Design 8	0.5	3.81
Design 9	0.9	2.29
Design 10	0.5	3.81
Design 11	0.6	4.89
Design 12	0.8	7.34
Design 13	0.8	6.21
Design 14	0.8	7.20
Design 15	0.8	6.15
⋮ ⋮		
Design n		

The resulting, trade-off curve number three is shown in Figure 6.34. It guides the engineers to potential design solutions as elaborated in previous projects best conforming to weight and package. Moreover, it shows the appropriate sheet metal thickness on the given decision criteria. For example, although aluminium has the largest wall thickness, it achieves better weight to package ratios; hence the density is approximately one third compared to steel, as previously shown in Table 6.10.

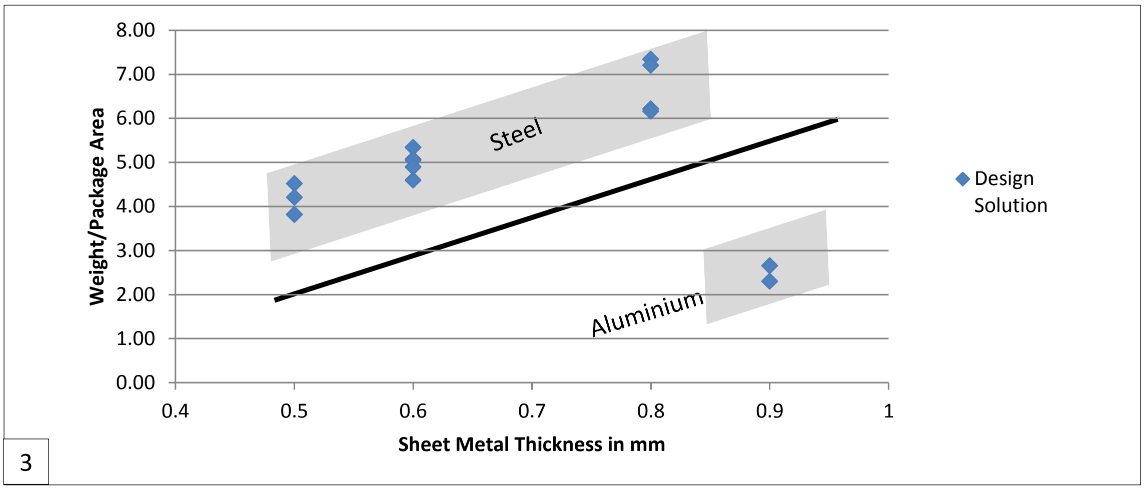


Figure 6.34 Trade-off Curve Three - Relation between Weight to Package Decision Criteria of Previous Design Solution and Sheet Metal Thickness

A usual scenario during concept design occurs when the engineer verifies the proposed design solution via crash simulation. In case the proposed design solution fails, the engineer usually increases the wall thickness on the sheet metal to increase the value realisation on the durability decision criteria. However, by increasing wall thickness, the weight and therefore also cost increase in proportion to the added thickness.

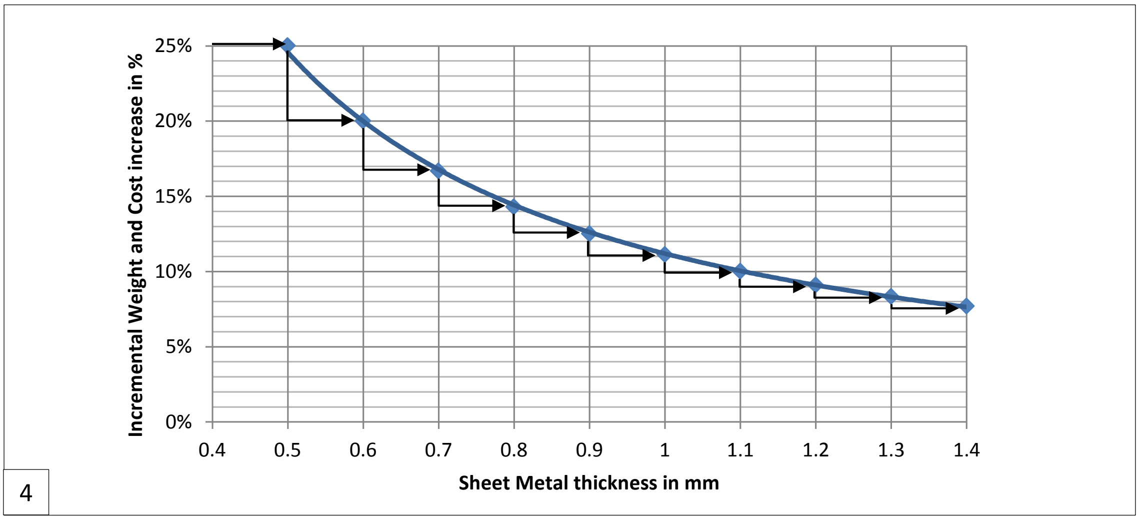


Figure 6.35 Trade-off Curve Four - Weight and Cost Decision Criteria increase related to incremental Sheet Metal Increase on Constant Surface Area

Consequently a fourth trade-off curve was created to visually display the incremental increase in sheet metal weight and cost when adding 0.1mm thickness on the proposed design solution, as shown in Figure 6.35. This aims to inform engineers about the design implications upfront to computational simulation. For example, if the engineer changes the wall thickness from 0.5mm to 0.6mm, the increase in weight and cost of the sheet metal equals 20%.

6.3.3 Knowledge Representation: Stage 3 of the LeanKLC in Case Study 2

Task 3.3 Formally Represent Captured Joining Knowledge

The task of formally representing captured knowledge was accomplished using decision trees in order to equip product designers and engineers with the logic as well as the sequence of decision making for a particular joining process. The example of a laser beam welding rule is illustrated in Figure 6.36.

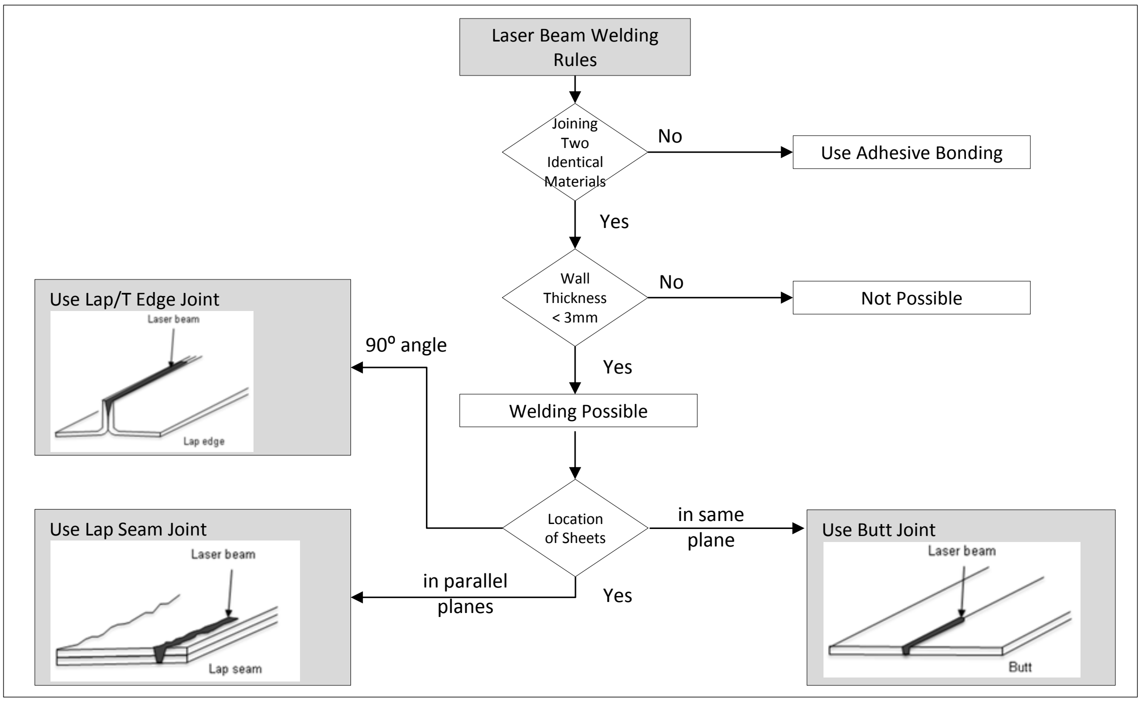


Figure 6.36 Representation of Laser Welding Knowledge using Decision Trees, Rules adapted from Herran Mungia (2011)

The decision tree encompasses three decision elements. The first decision element comprises the necessity of joining two identical materials, otherwise the engineers shall consider adhesive bonding. The second decision element informs the engineer that laser beam welding is only possible on sheet metal with a wall thickness smaller than 3mm. The third and final decision element suggests to the engineer the most efficient laser beam processing based sheet locations. For example, in the case of sheets located in parallel planes, the engineers should use a lap seam joint in order for the laser to operate vertically. Using the decision tree, as illustrated in Figure 6.36, provides the representation of knowledge with regard to key decision making during the product design and development of car seat structures.

6.3.4 Knowledge Sharing: Stage 4 of the LeanKLC in Case Study 2

Task 4.1 Centralise captured Joining Knowledge

Knowledge is available to the product designers and engineers via the product data management system. The use of the PDM system aims to provide the technological information engineers require to design and develop a product. Its main source of knowledge are CAD models stored according to a Bill Of Materials (BOM) structure including technical information related to part assembling constraints. This means that engineers accessing CAD data in different phases and function are able to retrieve geometrical models according to uniform geometrical constraints based on proven knowledge.

Task 4.3 Share Knowledge through Visualisation in Company B

Trade-off curves are used to share knowledge through visualization. Real case trade-off curves are created to enable product design and development engineers to extract important material properties in one simple graph as opposed to documented knowledge in lengthy reports. In addition, sharing such knowledge with the manufacturing department during stage gate reviews is used to eliminate over the wall communication. The use of real case trade-off curves during set narrowing is explained in Section 6.3.6.

6.3.5 Knowledge Integration: Stage 5 of the LeanKLC in Case Study 2

Task 5.1 Gather Functional Requirements in Company B

During requirements gathering, as explained in Section 4.2, company B expressed that any form of knowledge system must be based on the currently used CAD system CATIA V5. Accordingly, the system architecture to support the KBE prototype development is based on the currently used CAD system and explained as follows.

Task 5.2 Adapt a System Architecture to Develop a KBE Prototype

CATIA V5 contains a module, knowledgeware, to verify design solutions against rules and constraint based knowledge using macros in visual basic programming language (Cozzens, 2004; COE, 2005). Consequently, company B adapted such module to develop a KBE system based on the system architecture, as illustrated in Figure 6.37.

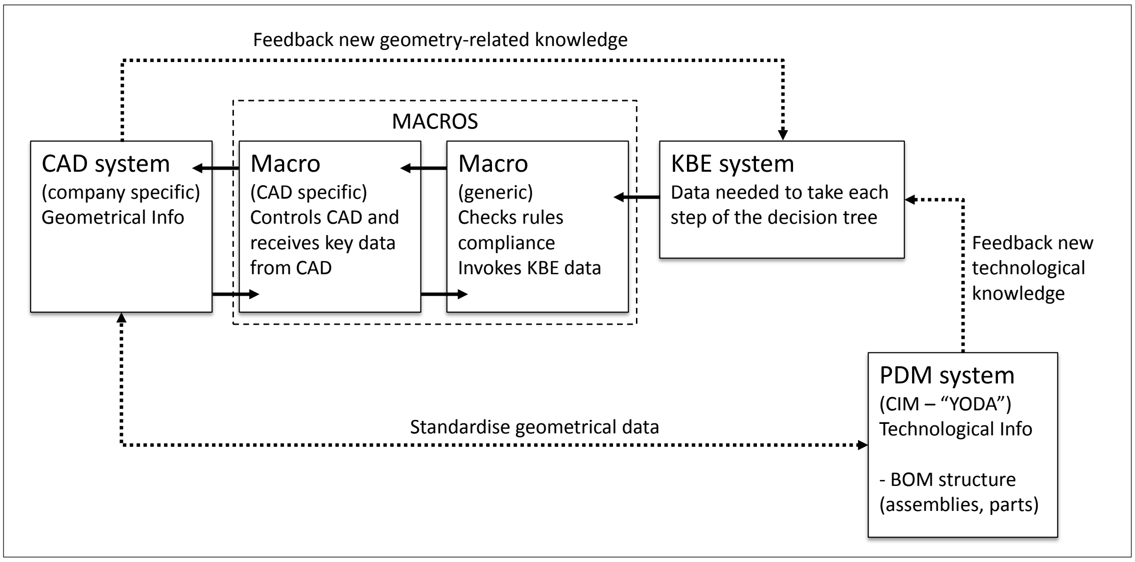


Figure 6.37 Knowledge Based Engineering System Architecture to develop KBE prototype in Company B (Sorli et al., 2012)

In the system architecture PDM comprises the centralized storage medium containing technological information of which BOM data structure is coherent with geometrical modelling in the CAD system. As such, the KBE system retrieves technological knowledge from the PDM system as contextualized in the decision trees resulting from knowledge representation in Section 6.3.3. This is achieved by using macros within the knowledgeware modules of which macros check generic rule compliances, as illustrated in Figure 6.36. In addition, CAD specific macros control the actual modelling by retrieving geometrical information from the CAD model during product design. Once the engineer changes the CAD model, new geometrical information is compared within the KBE system until the design is finalized.

6.3.6 Knowledge Use and Provision: Stage 6 of the LeanKLC in Case Study 2

The development of a KBE system during case study 2 aims to enable engineers to use the captured knowledge in the form of design rules and constraints during the actual computer aided design activity by retrieving knowledge from the centralized PDM system. Figure 6.38 illustrates a snap shot of the system in use in which the current design is compared against the captured spot welding design rules.

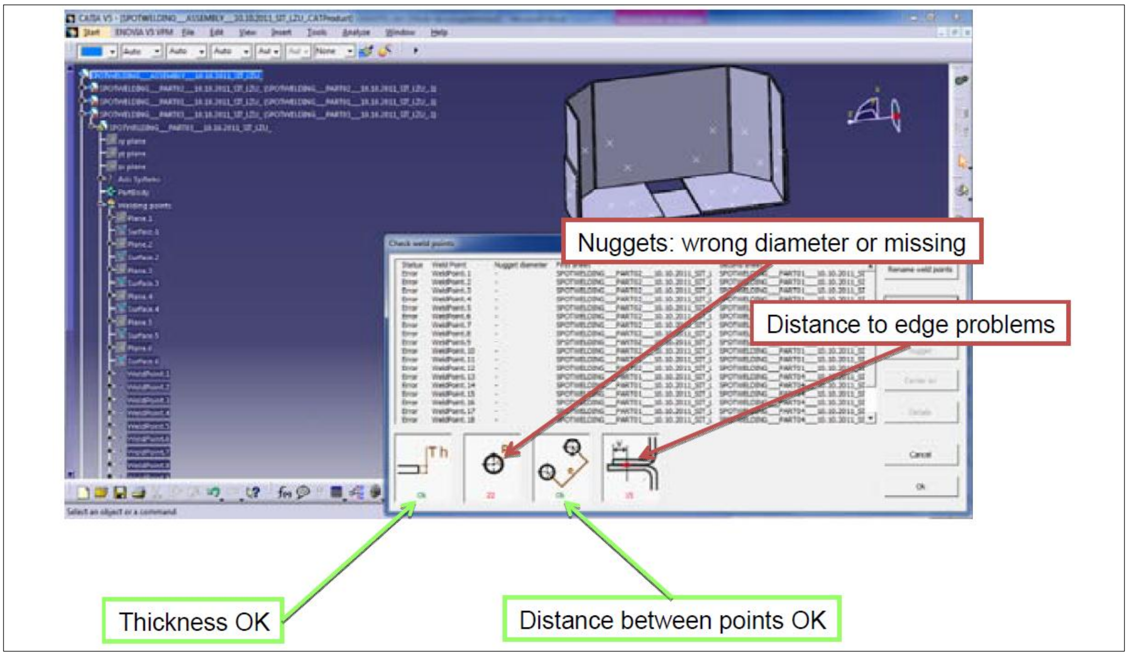


Figure 6.38 Design Rule Knowledge Use in CATIA CAD system (Sorli et al., 2012)

In this particular example, Figure 6.38, engineers are informed that the thickness of the chosen sheet metal well as that distance between the points is according to the design rules. More importantly, the system indicates that some of the nugget diameters are not in relation to the wall thickness. In addition, it outlines that a particular geometry does not comply to the distance to edge rule which causes collision with the electrode during manufacturing, as similarly illustrated in Figure 6.31. In both instances the system indicates the areas of non-design rule conformity but also displays the correct design rule in a separate window. However, modifying the design accordingly remains the duty of the product designer in order to realise knowledge use.

To date the system is in use and further developed to such an extent that the maximum amount of spot welds are generated on a given joining area. This aims to provide product designers an initial amount of correctly mounted spot welds to significantly shorten such mundane tasks. Nevertheless, product designers modify, eliminate and relocate spot welds as well as product geometry in order to find an optimal solution, which again requires a system to prove conformity to the captured design rules.

Task 6.1 Use Trade-off Knowledge during Set Narrowing Phase when designing Car Seat Structures

The four trade-off curves as developed in task 2.3 (Section 6.3.2) are used to enable company B to initiate potential design solutions but also to proceed during set narrowing, as illustrated in Figure 6.39. Accordingly, trade-off curves numbers one, two and three aim at supporting the generation of alternative design solutions as well as supporting the knowledge sharing between different design solutions in vertical (Y) dimension. Trade-off curve number four on the other hand, comprises the knowledge required to support proceeding during set narrowing in horizontal (X) dimension as shown in Figure 6.39, by visually displaying the impact on weight and cost when modifying the potential design solutions.

As a result, set narrowing using trade-off curves is accomplished by firstly providing one design solution based on value realization among different decision criteria and secondly to support proceeding to the next phase of set narrowing. As shown in Figure 6.39, design1 as initiated based on trade-off curve one, realizes customer value based on the cost decision criteria, whereas it performs weakly in terms of durability decision criteria. Design2 on the other hand fully realizes the durability decision criteria, meaning that through set narrowing using trade-off curve number four a design solution is generated compiling both decision criteria to a high realization score. Design3, as shown in Figure 6.39, was elaborated using trade-off curve number three and consequently scores highly on realizing two decision criteria, these being weight and package.

The set narrowing, as illustrated in Figure 6.39, continues with design3 and design4 in the same routine until an optimum design is elaborated best realizing the decision criteria for designing car seat structures. Given the above, using trade-off curves in set narrowing is contextualized in case study 2 and as such completes stage 6 of the LeanKLC application.

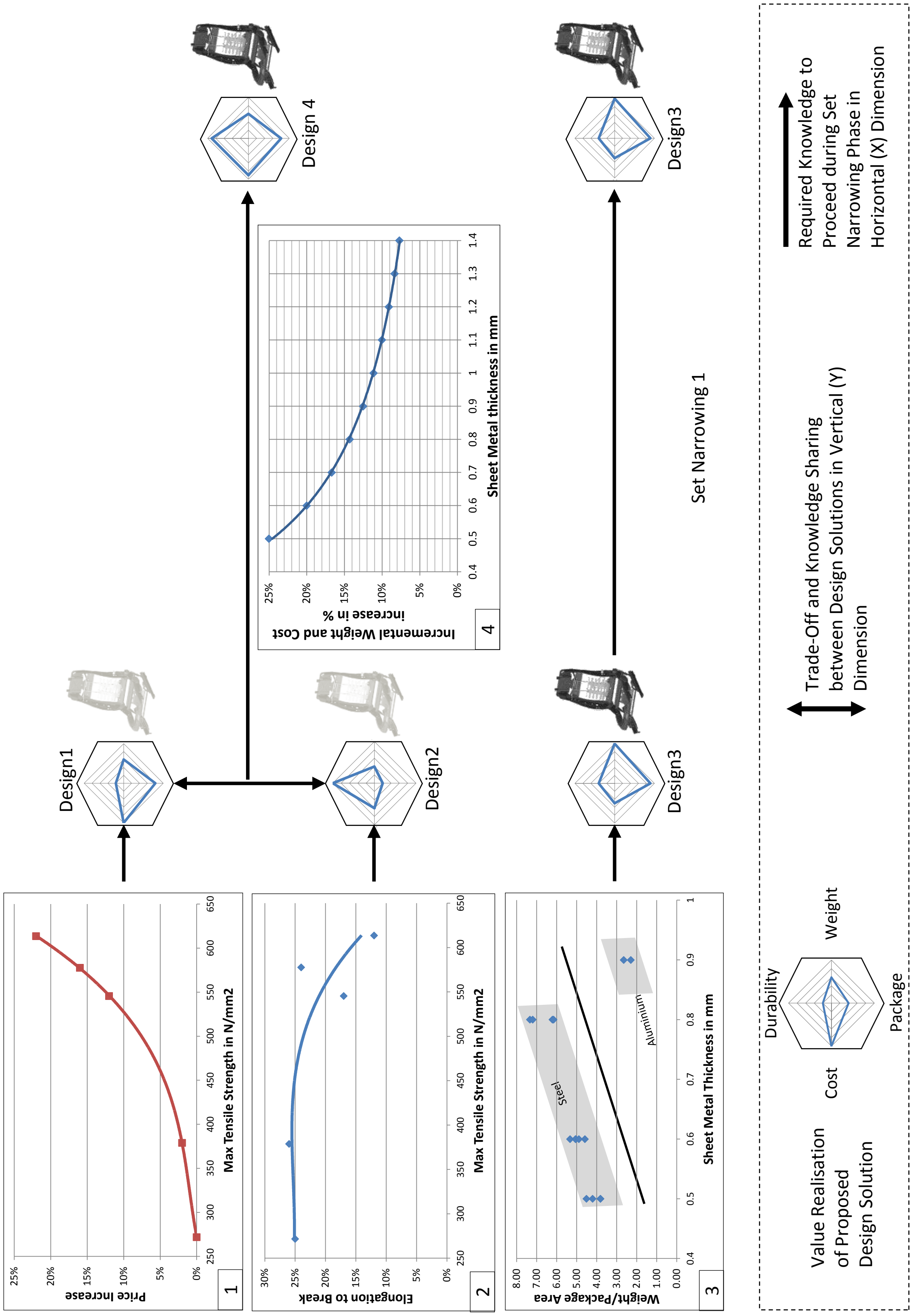


Figure 6.39 Contextualisation of Using Trade-Off Knowledge during Set Narrowing in Company B

6.4 Chapter Summary

This chapter demonstrated the industrial application of the LeanKLC in two industrial case studies, each addressing one of the two LeanKLC streams. It is evident that the LeanKLC as a sequence of stages as well as its underlying framework has different facet when applied in different domains or business functions. In both cases commitment of the stakeholders was vital to achieve a continuous loop of LeanKLC stages and most importantly, the continuation in the form of dynamic knowledge capturing. Chapter seven following presents the discussion and conclusion of the work presented research.

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Chapter 7

DISCUSSION AND CONCLUSIONS

7.1 Introduction

The thesis arrives at the final Chapter 7, entitled Discussion and Conclusions. The chapter starts in Section 7.2 with a discussion of the research findings followed by outlining the contribution to the scientific body of knowledge in Section 7.3 and the research limitations in Section 7.4. To end, Sections 7.5 and 7.6 highlight the main conclusions and potential future work of the research presented in this thesis.

7.2 Discussion of Research Findings

The discussion presents a critical reflection on the results found in this research. It discusses findings related to the need of a knowledge environment in lean product development, the research design and methodology, the LeanKLC framework development and the case study validation.

7.2.1 The Need of a Knowledge Environment in Lean Product Development

The reviewed literature outlines that the knowledge environment is one key enabler of the LeanPPD paradigm, along with value-focused planning and development, continuous improvement and chief engineer (Al-Ashaab, 2012). It is a fact that all the research to support product development using lean thinking acknowledges (in most cases randomly) the importance and the provision of a knowledge environment. Hence, a rigorous implementation of LeanPD cannot be achieved without having an adequate knowledge environment, which on the other hand requires an underlying framework to identify, capture and re-use the knowledge during product development. In order to provide more insights, this study presented an extensive collection of tools and techniques as identified in the current LeanPD literature and also their classification into four areas related to the knowledge environment, these being decision making, centralised knowledge, visualisation and problem solving.

This research also reviewed in detail in Chapter 3 the different currently available KLCs (e.g. Buckowitz and Williams, 1999; Stokes, 2001; McElroy, 2003; Dalkir, 2011). The review however, concluded that knowledge life cycles were mostly interested in manifesting theoretical arguments rather than thoroughly investigating or describing closed loop industrial case study applications. More importantly, addressing the issue on knowledge life cycle related to LeanPD and providing a detailed framework has not as yet, been thoroughly addressed. As a consequence, this research has presented a novel Lean Knowledge Life Cycle (LeanKLC) framework to provide the correct knowledge environment to enable a truly LeanPD implementation.

7.2.2 Research Design and Methodology

The novel research, required a methodology to be adapted that enabled the researcher to address its objectives. However, the subject area investigated appeared not only very complex but also unexplored at the same time, meaning that one single method could not result in adequate data collection. The researcher also believes that the LeanKLC could not have been developed without having employed such an extensive as well as aggressive research approach, as explained in Chapter 2.

The extensive scientific literature review provided a snapshot of what is currently available as well as understood by scholars and practitioners. This was supported by undergoing a rigorous key word search pattern mainly to depict those publications related to lean or product development within the widespread and rather philosophical discipline of knowledge management. Understanding the literature helped the researcher to identify the direction in which to approach the industry.

In practical terms however, once the research involved the participation of industrial partners, it turned out that the language jargon used in the literature could not be directly transmitted to product designers and engineers. Also, product development featured a high variety and ever changing technology driven process. Consequently, knowledge would evolve alongside such a dynamic and complex environment. This understanding enabled the researcher to differentiate elements of philosophical thinking in the reviewed literature from the apparent reality in real industrial product development.

In order to provide evidence and construct valuable arguments, data collection using questionnaire, focus group and expert judgement was conducted largely using action research. This extensive data collection revealed a certain repetitive pattern among product designers and engineers in which they expressed key concerns with regard to managing product development knowledge. Capturing such statements was highly time intensive, though vital for the researcher to create a clear map of an extended range of apparent challenges based on empirical first hand data collection. Arguably the capturing, classification and ranking of challenges based on thematic coding, illustrated in Table 4.4, is in fact the most valuable result of the entire data collection effort.

7.2.3 Lean Knowledge Life Cycle Framework Development

Developing a novel LeanKLC demands that the research is required to go beyond the traditional KLC approaches. Table 7.1 illustrates a comparison of traditional KLC, as reviewed in Section 3.5, against the novel LeanKLC developed in this research and presented in Sections 5.2 to 5.6. However, the author does not intent to form generalisations from traditional KLC approaches; moreover, Table 7.1 aims to highlight key differences as addressed during this research in order to provide transition to a LeanPD knowledge environment.

Even though traditional knowledge life cycles provide insightful approaches for corporate knowledge management, to date its application in product development was revealed to be under-represented. Though it was easy for scholars to claim that knowledge is important, a contextualisation of the existing dimensions of managing product development knowledge was established for the first time during this research in Section 5.2. Moreover, it provided evidence on how an acclaimed LeanPD process model conforms to the proposed three dimensions of knowledge management in a product development baseline model. This multidimensional view provides the baseline model of the novel LeanKLC to propose a framework particularly suitable for the LeanPD by contextualising for the first time horizontal, vertical and previous knowledge sharing to claim a truthfully development of knowledge environment. Furthermore, the author believes that the baseline model qualifies the LeanKLC to be adapted to any lean product development process that follows sequential phases or activities.

Table 7.1 Comparing Key Findings from Traditional KLCs versus novel LeanKLCdeveloped in this Research

Criteria	Key Findings from traditional KLCs (Chapter 3, section 3.5)	Developed Novel LeanKLC (Chapter 5, sections 5.2 to 5.6)
Scope	- High Level Corporate KM	- LeanPD
Approaches to KLC Framework Development	- Based on several predefined topics - Modifying previous work by integrating additional elements - Reconsideration or enhancement of initially proposed frameworks	- Knowledge environment in LeanPD - Frontloading key stakeholders concerns in PD - Synthesising a novel three dimensional baseline model with acclaimed LeanPD process models
Techniques	- Extensive range of theoretical models and techniques accumulated to date	- Selected range of techniques chosen as collected from LeanPD literature to support key stages of the LeanKLC
Knowledge Identification	- Several approaches suggested for knowledge identification	- Definition of indicators for useful knowledge identification in PD
Knowledge Capture	- Lack of ergonomic processes and tools to capture knowledge during PD - Structured knowledge capture templates used to solve domain specific problem	- Novel perspective and principles elaborated for dynamic knowledge capture during PD - Technique and template to dynamically capture knowledge during PD problem solving using A3LAMDA
Knowledge Representation	- Extensive range of potential knowledge attributes available	- Four key knowledge attributes for the LeanPD knowledge environment
Knowledge Sharing	- Knowledge visualisation using symbols, pictures and metaphors for generic concepts	- Knowledge visualisation using A3LAMDA report and trade-off curves
Knowledge Integration	- Integrating organizational knowledge across the enterprise	- Integrating knowledge in the PD process
Knowledge Use and Provision	- Largely anticipated state of right knowledge provision at right time and place - Knowledge use contextualised during different modes of knowledge conversion	- Evidence in form of graphical representation for right knowledge provision at right time and place in PD using vectors - Knowledge use contextualised during SBCE process using trade-off curves

Another novelty as opposed to traditional KLCs is the front loading of industrial challenges in managing product development knowledge. As such, the stages of the LeanKLC have been chosen with regard to corresponding challenge categories raised as a result of repetitive patterns during first hand data collection from key stakeholders, namely product designers and engineers.

This PhD research project encompasses two LeanKLC streams, A3LAMDA and trade-off curves, as main set of techniques investigated to facilitate the LeanPD knowledge environment. Exploring the entire set of LeanPD techniques, as illustrated in Table 5.2, requires more thorough investigation of the inaccurately explained techniques in the LeanPD literature and more importantly further research into detailing certain tasks according to each stage of the LeanKLC. Nevertheless, this research provides the foundation in order to initiate such potential future work.

The principle of dynamic knowledge capture, as elaborated in Section 5.5.2 forces the knowledge management community to go beyond monolithic perspectives of case based knowledge life cycle applications. Knowledge capturing in the LeanPD knowledge environment is set to be accomplished whilst actually developing a product, a novel perspective which puts key stakeholders in charge of upgrading the knowledge base in a dynamic manner.

It can be argued that in many instances the LeanPD community takes knowledge for granted. In reality however, such knowledge must be captured in the first place before it can be re-used. Therefore, this research provides the awareness that to begin with, previous knowledge must be captured in order to provide an early knowledge environment. This largely refers to the case of trade-off curves. It is easy to claim that trade-off curves are used to display knowledge, although the real difficulty is to capture adequate knowledge which truly supports decision making. Therefore, this research outlines the necessity of defining important decision criteria before capturing knowledge to create trade-off curves.

Lean knowledge management termed as a practice to provide the right knowledge at the right time and place (Kennedy et al., 2008; Rooke et al., 2010) requires a profound theory and technique that demonstrate its practicality in product development. For this reason, Section 5.5.3.2 explains a novel technique to graphically represent knowledge provision in order to visually display the right knowledge at the right time and place using vectors.

Although the development of the LeanKLC was a significant step forward towards developing a framework towards a knowledge environment, it still does not address the whole extent of potential LeanPD applications. Nevertheless, the LeanKLC framework developed ended with successful case study validation, as will be discussed in the following section.

7.2.4 Case Study Validation of the LeanKLC

7.2.4.1 LeanKLC Application in Case Study 1 – Company A

Case study 1 demonstrated the practical aspect of the LeanKLC in a real industrial environment to solve Electromagnetic Compatibility (EMC) problems and dynamically capture knowledge by following those tasks allocated to the A3LAMDA stream. This however, required changing a large extent of the workflow of the current product development process in order to have independent design verification and validation in an automotive company, as shown in Figure 6.4.

The remarkable aspect of case study 1 is that the theory of dynamic knowledge capturing, as envisioned in Figure 5.9, was accomplished in practice as illustrated in Figure 6.5. This needed customisation of the enhanced A3LAMDA template, such as structuring most apparent EMC design issues in the enhanced root cause analysis in order to reduce time to understand the problem and find a proposed design solution. In addition, it required a process to integrate dynamic knowledge capture during problem solving as a result of lessons learnt amongst the collaborative design team. In total six A3LAMADA reports have been completed on five different projects to provide clear evidence for construct validity of the developed A3LMADA LeanKLC stream.

During the industrial application of the LeanKLC in case study 1, mainly recommendations, as opposed to design rules, have been captured dynamically in the A3LAMDA reports. This highlights that in the particular domain of EMC, engineers are less capable of documenting explicit knowledge as a result of problem solving.

A total of 10 design solutions needed to be proposed and verified in order to produce six design solutions that actually solved the problem. This illustrates the evidence that the initiation of multiple design solutions will create new knowledge, an agreed perspective among the SBCE community. In two instances however, the design solving team could not find a permanent solution. Nevertheless, indication is given regarding those critical solutions where continuous improvement is required.

Most of the knowledge needed attributes P_{nd} were declared in other functions than electrical engineering, the function where the problem solving activity was originally initiated. This means that the full spectrum of the three dimensions of knowledge management in product development was understood and considered by the engineers during case study 1. Accordingly, the provided knowledge was rated useful by those who utilised it in both instances.

The knowledge environment in case study 1 was largely manifested by the capability of sharing knowledge during problem solving in a multidisciplinary team. In particular, this implies to element number 7 (prevent recurrence) of the enhanced A3LAMDA template to instantly share knowledge of implemented design solutions to those affected products and processes.

The resulting knowledge base of the completed A3LAMDA reports outlines that as the amount of knowledge captured increases, it will be difficult to manage without supportive software. Nevertheless, the experience of case study 1 has proved the feasibility of having an automatic and structured knowledge capture template using A3 thinking in order to manage and maintain resulting knowledge in a useful way.

To sum up, involving engineers in the process of dynamic knowledge was successfully accomplished. It shows that engineers are willing to participate in the mundane process of documentation only if it is facilitated to such an extent that it adds value to the daily routine as encountered by product designers and engineers. Moreover, it provides evidence of a closed loop LeanKLC application using A3 thinking to solve engineering problems and create new knowledge in a LeanPD knowledge environment.

7.2.4.2 LeanKLC Application in Case Study 2 – Company B

Case study 2 presented the application of the in trade-off curves LeanKLC stream as well as the development of a KBE prototype by following the key stages of the LeanKLC.

It can be argued that trade-off curves are already used in product development; however, this case study provides evidence of how to capture and re-use trade-off knowledge in a real industrial environment. It was observed that product development engineers favour the simplicity of the approach, the technical relevance as well as the fact that most of the knowledge is captured from previous projects. Case study 2 also presented a scenario for how to use real case trade-off curves during set narrowing when designing car seat structures. The use of trade-off curves is envisioned to have significant impact to facilitate the initiation of different set of design solutions and provide product development engineers with a considerable step towards a LeanPD knowledge environment. After the completion of case study 2, company B employed a follow-up knowledge capture initiative based on physical durability testing in order to create trade-off curves that display crash performance among different joining patterns.

7.2.4.3 LeanKLC Application in Case Studies 1 and 2

The interpretation of research results from case studies 1 and 2 provide evidence on construct validity of the LeanKLC, applied within two different knowledge domains, these being electromagnetic compatibility and joining methods. This was demonstrated in both of the developed LeanKLC streams, namely A3LAMDA in case study 1 and trade-off curves in case study 2. Although the LeanKLC was presented as a generic framework, its application takes different shapes depending on the knowledge domain, objectives and scope of industrial application. Hence, companies are given the opportunity to gradually explore potential benefits of the LeanKLC and accordingly apply further tasks as the scope of application increases. For example, it is possible to undergo LeanKLC stages 1 and 2 only in order to explore the depth as well as lack of existing knowledge rather than applying the entire stages of the LeanKLC at once.

Whilst dynamic knowledge capturing was accomplished in case study 1 (see Figure 6.5), the transition from previous to dynamic knowledge capture did not take place in case study 2 (see Figure 6.28). Even though the LeanKLC allocates a task to explore ways of dynamic knowledge capturing for the LeanPD knowledge environment in Section 5.5.2.4, the accomplishment of its desired state outlines different time implications based on the scope of individual case studies. This largely refers to the required action research in order to develop and integrate a customised dynamic knowledge capturing template based on the techniques put forward by the LeanPD community.

7.3 Contribution to Knowledge

Contribution to knowledge in scientific research is largely manifested by investigating the research gaps as identified in the current body of knowledge. Accordingly, the following presents the author's key contributions to the scientific body of knowledge:

1. Capturing, classification and detailed description of 38 industrial challenges in managing product development knowledge based on empirical first hand data collection from key informants.
2. A baseline model entailing the three dimensions of knowledge management in product development as well as its contextualisation with acclaimed LeanPD process models.
3. A novel Lean Knowledge Life Cycle (LeanKLC) framework developed including detailed description of sequential stages, tasks and supporting techniques to provide a suitable knowledge environment to enable a truly LeanPD implementation.
4. Definition of four key knowledge attributes and the development of a novel technique to graphically represent the right time and place for knowledge provision during product development.
5. The advanced perspective and principles of dynamic knowledge capture as well as its utilisation during problem solving alongside the enhanced the A3LAMDA template.
6. An extended understanding of how product development knowledge can be captured using trade-off curves based on decision criteria. Moreover, a concept to showcase how the use of trade-off knowledge supports concept selection during set narrowing in LeanPD.
7. Two LeanKLC industrial case study applications, providing empirical evidence regarding the transformation towards a knowledge environment to support LeanPD implementation.

7.4 Research Limitations

In order to outline possible negative consequences that affect the generalizability from the previously discussed research findings, the author expresses the following research limitations.

1. Subjectivity - One of the critiques in qualitative research is subjectivity. In particular the abstract explanation in the current LeanPD literature conveyed

opportunities for the researcher to occasionally prioritise personal interpretations and perspectives when developing a LeanKLC to support the LeanPD. Hence the close collaboration with industry in particular through case study validation ensured that the developed framework corresponds to the technical relevance as apparent in product development.

2. Bias - Although the author conducted face to face interviews and obtained expert judgement to reduce bias during data collection, predispositions still occurred among the participants, in particular related to knowledge management. Especially during data collection in the industrial field study participants had different perceptions of what knowledge actually is. In fact it was vital to provide tailored terminologies for knowledge itself, before interacting with certain groups of product designers and engineers.
3. Level of group dynamics - A limitation that is difficult to avoid during the conduct of focus groups. This has led in some cases for the influence on groups of participants to change opinions regarding the subject under discussion. In particular it had somewhat negative influence on the initiation of further case studies among the industrial collaborators during the research.
4. Confidentiality - Although industry was heavily involved in the research, companies were collaborators in the first place and access to some of the critical product development data was denied due to reasons of confidentiality. Hence, the case studies explained in Chapter 6 entail an approved content of information gathered during the LeanKLC application.
5. Scope - The research results are limited to the scope of a product development process (from concept design to production) and its key stakeholders, namely product designers and engineers. It does not take the entire product life cycle into account, such as marketing, purchasing, disposal and maintenance. In addition it was only applied to large companies that have a mature product development process, meaning that SMEs have not been considered during the research.

7.5 Conclusions

After the extensive qualitative research employed in the related disciplines of knowledge management and lean product development the author draws the following conclusions:

1. The truly LeanPD implementation cannot be achieved smoothly without the provision of a suitable knowledge environment. Therefore, this study has provided a novel, well-structured LeanKLC framework to contribute and enable the LeanPD implementation for this particular core enabler.
2. Up to the present time, managing product development knowledge still remains a significant challenge for scholars and practitioners. Whilst the product development community struggles to move from task based to a knowledge based environment, the knowledge management community is slow in integrating its philosophical principles to the technical product development environment.
3. The industrial field study indicated that tacit knowledge is the most important source of knowledge in product development. Hence knowledge sharing, in order to provide an environment that facilitates tacit knowledge conversion among product designers and engineers, is equally as important as the attempt to capture and articulate tacit knowledge.
4. Whilst scholars and practitioners anticipate the state to provide the right knowledge at the right time and place, its realisation is largely dependent on accurately declaring the attributes of future need which is accomplished during knowledge capturing. Therefore, the application of dynamic knowledge capture requires increased attention during product development to realise such anticipated state.
5. Product development is largely manifested by intuitively solving problems in order to modify previous design solutions until utilising given decision criteria. In order to create new knowledge as a result of problem solving, multiple potential design solutions are required to be proposed and verified. These experienced conditions indicate that the two developed LeanKLC streams, A3LAMDA and trade-off curves, would support each other's application, despite the fact that they have been validated separately during this research.
6. The abstract description of principles and techniques explained in the current LeanPD literature demands from the industry engagement in empirical research to realise any form of LeanPD transformation.
7. The required knowledge environment for LeanPD is a wide subject area that has not been thoroughly understood to date. This study has provided the base line research in particular by illustrating the different dimensions of knowledge management that need to be considered in such an environment.

7.6 Future Work

It would be against the principle of continuous improvement to claim that the author has reached the end of the road with this work presented research in terms of the LeanKLC. On the contrary, it offers new opportunity for more empirical research in order to build upon the research findings and increase the contribution to knowledge in the evolving discipline of LeanPD. The identified areas particularly suitable for future research are:

1. The expansion of the three dimensional baseline model to those knowledge sources acquired outside the company, such as suppliers and contractors, as an additional element in the vertical Y dimension.
2. The development of a technique and template to dynamically capture trade-off knowledge during product design and development. This would aim to provide further empirical evidence on dynamic knowledge capture beyond the A3LAMDA stream.
3. The development of further LeanKLC streams according to the tools and techniques discussed in LeanPD literature in order to cover a wider spectrum of the knowledge environment.
4. The allocation of different roles to be responsible as well as addressing the social dimension for implementing the LeanKLC in industrial scale. These could include a KM champion who oversees the full initiative as well as a KM officer who coordinates the work to product development personal in the different stages of the LeanKLC.
5. Although key knowledge attributes have been suggested as particularly important for the LeanKLC, the consideration of knowledge retrieval and search capability was not explored and provides opportunity for future research.
6. The application of the LeanKLC in more case studies covering sectors in addition to the automotive, such as aerospace or pharmaceuticals.
7. In order to establish a comprehensive and among the research community well agreed definition of LeanPD, the interrelations of its core enablers including the knowledge environment require thorough explanation in future research.

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APPENDICES

Appendix A Requirements Gathering for a Knowledge based Environment

LeanPPD Requirements Template

LeanPPD Workpackage	**WP300: Knowledge Based Engineering for Lean Product & Process Development**
Objective Workpackage / Task:	**Knowledge Based Environment**
LeanPPD partner in charge	**Cranfield University**
template was filled in:	**23/09/2009**

A) Functional Requirements: A sentence that describes the functionality of the solution that will solve the industrial partners' problems. Requirements identify the functions that satisfy identified needs for the LeanPPD companies. Requirements usually start with a "verb" and describe an action that the tool should do or provide.	**A) Relevance (1 = no relevant to 5 = very relevant)**					**B) Feasibility to implement within the company (1 = low feasibility to 5 = high feasibility)**					**C) CONSTRAINTS: Please identify potential constraints to implement the requirement in your company**	**D) VALUE FOR PRODUCT DEVELOPMENT: Please describe the value of the requirement for your company. Why is this requirement important to fulfil your company product development needs to become lean?**	**E) STAKEHOLDERS / USERS: Please identify the potential users. You can provide name/number of persons, internal company departments, suppliers, top management, etc**	**F) USABILITY: Identify the degree of expertise of the users and kind of interaction with the systems in order to identify measures that minimize the effort needed for use of the solutions depending on the rank of users.**	**G) SUCCESS FACTORS: How can you measure the "success" of the implementation of the requirement within your company? Which could be critical success factors for the implementation**	**H) Additional Comments / Remarks mentioned by the Five LeanPPD industrial partners**
Please enter in the cell a number from 1 (very low) to 5 (very high) for "relevance" and "feasibility" for each specification per requirement	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**						
Requirements 1: The KB Environment shall bring together relevant previous projects in order for the designers to initiate a new set of designs.																
1.1 The KB Environment shall capture and structure previous projects in order to have a standardised project knowledge repository to support new projects (e.g. CAD files, BOM, lesson learnt, Specification etc.)	5	5	4	4	3	4	3	4	2	4	Company A: The main constrait is how to organize data. Previous projects should be analysed in order to extract meaningful data that can be reused. Their organization should reflect the product structure (part, sub-assembly, assembly), the product or part functions, the bussiness lines, etc. Company B: This depends on the technology being used to deliver this functionality. Data format issues and legacy systems will provide huge challenges to complete this task. Company D: If it is structured by project alone we do not think will help SET Based Design. i.e. a new project may may require aspects from a completely un-related previous project. In an ideal world it would retieve knowledge from all the existing systems in a company. However, we realise that a prototype may be needed to store knowledge seperately to demonstrate the functionality. However, if it is separate from existing systems, this maybe a baCompany Bier to introduction. Not sure on how easy to implement until we see the solution. Needs to be as easy to use as the Engineer's log book, but have much better connectivity to a KBE. Company E: It could be difficult to gather solely useful information to support a prospective innovation process. Another hurdle is to store information universal retrievable.	Company A: It will makes easier the retrieving of data from the implemented PLM system. It will improve knowledge reuse and management Company B: Capturing & structuring and storing knowledge so that it can be easily re-used is key to a lean product and development process. Company E: To capture all relevant information about previous projects in a well-regulated, easy accessible database is the aim of the most companies and this could increase the efficiency of processes.	Company A: Designers and Engineers coming from the different R&D departments that develop Company A bussiness lines Company B: All engineering functions and knowledge engineers. Company E: Designers, Development Engineers	Company A: Users are experts as they are engineers and designers that use to develop product designs by elaborating previous CAD models., by analysing previous experimental tests results, etc. The main problem is the retrieving of the proper information for the specific context of work. The KM environment should facilitate documents retrieval by selecting meaningful words relating to product functions, contexts, etc. Company B: The solution should be architected so that it self configures itself based on the fidelity of knowledge requested. This will enable all users to interact with the system. Company E: System - Administrators should have an extensive acquaintance about product developement, technical specifications, CA - systems and database management to prevent an over - information and garbage in the database.	Company A: By measuring time for data retrieval and product design development. By comparing the results achieved by the KM environment and by the adopted PLM Company B: If projects or knowledge engineers use it then it is a success. Company E: The feedback from the CA - system users is critical in this term. Farther the success could be assessed by developement times, costs and product quality. The engineers will only use a system wich helps them. So we only should monitor the use of the system.	Company B: The methodology for all tools within this deliverable should dictate the solution approach. Once the solution approach is agreed the technologies that will deliver the solution need to be decided. This analysis of technology options may require us to review the solution and methodology. Maximum use must be made of existing capable technologies rather than inventing new ones.
1.2 The KB Environment shall facilitate inter-relation of previous projects	3	4	4	5	4	3	2	4	3	2						

A) Functional Requirements: A sentence that describes the functionality of the solution that will solve the industrial partners' problems. Requirements identify the functions that satisfy identified needs for the LeanPPD companies. Requirements usually start with a "verb" and describe an action that the tool should do or provide.	**A) Relevance (1 = no relevant to 5 = very relevant)**					**B) Feasibility to implement within the company (1 = low feasibility to 5 = high feasibility)**					**C) CONSTRAINTS: Please identify potential constraints to implement the requirement in your company**	**D) VALUE FOR PRODUCT DEVELOPMENT: Please describe the value of the requirement for your company. Why is this requirement important to fulfil your company product development needs to become lean?**	**E) STAKEHOLDERS / USERS: Please identify the potential users. You can provide name/number of persons, internal company departments, suppliers, top management, etc**	**F) USABILITY:Identify the degree of expertise of the users and kind of interaction with the systems in order to identify measures that minimize the effort needed for use of the solutions depending on the rank of users.**	**G) SUCCESS FACTORS: How can you measure the "success" of the implementation of the requirement within your company? Which could be critical success factors for the implementation**	**H) Additional Comments / Remarks mentioned by the Five LeanPPD industrial partners**
Please enter in the cell a number from 1 (very low) to 5 (very high) for "relevance" and "feasibility" for each specification per requirement	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**						
Requirement 2 The KB Environment shall enable a search function in order to locate and retrieve the most relevant project information																
2.1 The KB Environment shall provide a mechanism based on knowledge discovery techniques to identify trends of solutions from previous projects	**3**	**5**	**4**	**5**	**4**	**2**	**4**	**3**	**2**	**2**	Company A: The tool should be able to formalize knowledge in a way that is near to the way adopted by the company to identify trends of solutions. The main problem is how to classify solutions, problems, to support problem-solving by using previous case studies Company B: If the solution is self contained and does not require searching across company databases and systems then it probably won't be difficult. However if the solution requires interaction with company systems/databases then it will be very difficult to achieve. Company D: Sounds good, but do not have enough background knowledge on knowledge discovery techniques to provide more comments on thisThis relies on the coCompany Bect application of keywords at knowledge capture. If the knowledge is captured by someone with less experience they may tag the incorrect keywords. Should present the most relevant first, but all the deatail should be available if desired Company E: Without rigourous definition of specific database keywords in the company it could be difficult to find ALL relevant information. How does the system know which information is relevant at which time?	Company A: It supports conceptual design, reducing time to design new solutions based on previous successful ones, reducing the number of design eCompany Bors as it improCompany D users knowledge and expertise Company B: as above Company E: To find reasonable information about previous projects in cuCompany Bent worksteps could save a lot of time and reduce rollback work.	Company A: Designers, Marketing staff, project managers Company B: as above Company E: s.a.	Company A: Low level of expertise. Company B: as above Company E: These interfaces should be intuitive operable.	Company A: By identifing usability metrics able to highligh the necessary mental workload to perform specific tasks, the efficiency of the system according to the companies needs, etc. Company B: as above Company E: s.a.	Company B: It is advised that existing tools both in-house and externally avaiable are inCompany Dtigated to provide this servive.
2.2 The KB Environment shall facilitate key word searches	**5**	**4**	**4**	**3**	**5**	**3**	**3**	**2**	**3**	**2**						
2.3 The KB Environment shall enable the user to retrieve all the relevant information for a specific component or subsystem.	**5**	**4**	**5**	**5**	**5**	**3**	**2**	**4**	**5**	**4**						

A) Functional Requirements: A sentence that describes the functionality of the solution that will solve the industrial partners' problems. Requirements identify the functions that satisfy identified needs for the LeanPPD companies. Requirements usually start with a "verb" and describe an action that the tool should do or provide.	A) Relevance (1 = no relevant to 5 = very relevant)					B) Feasibility to implement within the company (1 = low feasibility to 5 = high feasibility)					C) CONSTRAINTS: Please identify potential constraints to implement the requirement in your company	D) VALUE FOR PRODUCT DEVELOPMENT: Please describe the value of the requirement for your company. Why is this requirement important to fulfil your company product development needs to become lean?	E) STAKEHOLDERS / USERS: Please identify the potential users. You can provide name/number of persons, internal company departments, suppliers, top management, etc	F) USABILITY: Identify the degree of expertise of the users and kind of interaction with the systems in order to identify measures that minimize the effort needed for use of the solutions depending on the rank of users.	G) SUCCESS FACTORS: How can you measure the "success" of the implementation of the requirement within your company? Which could be critical success factors for the implementation	H) Additional Comments / Remarks mentioned by the Five LeanPPD industrial partners
Please enter in the cell a number from 1 (very low) to 5 (very high) for "relevance" and "feasibility" for each specification per requirement	Company A	Company B	Company C	Company D	Company E	Company A	Company B	Company C	Company D	Company E						
Requirement 3: The KB Environment shall provide a function to visualise knowledge required to support engineering decision taking																
3.1 The KB Environment shall provide a means of viewing the most important knowledge relevant to a problem encountered during the product development in a concise and easy-to-digest format	5	5	5	5	5	4	3	1	5	1	Company A: The tool should support knowledge formalization and visualization according to the different typologies of products designed and manufactured by the company (washing machines, refrigerators, dishwasher, ovens, etc.). Each business lines has its own parameters, structure, needs and hence knowledge (problems- solution) Company D: This should focus on more innovative ways of presenting and navigating through the results. It should not just be a list / google result. i.e. could be a spider / mind map where you can navigate in the direction of the information you find more relevant. The system should pull on the fundermental engineering relationship to optimize the solution, not just plug in previous solution that may not be optimised for this application. If an in-experenced engineer is accessing knowledge which is releated to the overall architecture of a product, there is a high risk that the knowledge will not be applied correctly. If a user is successful in adding and applying knowledge (without having knowledge corrected or without creating defective products) the user should be give greater rights in the system (similar to WIKIPEDIA) Company E: The system should access cautious. If the exposures about previous projects seem to dominant, innovations could be hemmed. Actual and prospective know-how must be concerned in the KBE.	Company A: Visualization represents a key factors in problem-solving. A proper data visualization can facilitate the creative process as well as the product development according to technical specifications Company B: as above Company E: To get reasonable information about previous projects in current worksteps could save a lot of time.	Company A: Designers and Engineers coming from the different R&D departments and the Information&Technology staff Company B: as above Company E: s.a.	Company A: Low level of expertise. Visualization should provide an easy way to undestand and use data Company B: as above Company E: These interfaces should be intuitive operable.	Company A: By measuring mental workload to interpret and elaborate achieved results and users satisfaction during data analysis Company B: as above Company E: s.a.	
3.2 The KB Environment shall provide a function to produce trade-off curCompany D, which illustrate the relationship between key characteristics and parameters of different design solutions from previous and cuCompany Bent projects	5	3	5	5	2	2	2	4	5	3						

A) Functional Requirements: A sentence that describes the functionality of the solution that will solve the industrial partners' problems. Requirements identify the functions that satisfy identified needs for the LeanPPD companies. Requirements usually start with a "verb" and describe an action that the tool should do or provide. Please enter in the cell a number from 1 (very low) to 5 (very high) for "relevance" and "feasibility" for each specification per requirement	A) Relevance (1 = no relevant to 5 = very relevant) Company A	Company B	Company C	Company D	Company E	B) Feasibility to implement within the company (1 = low feasibility to 5 = high feasibility) Company A	Company B	Company C	Company D	Company E	C) CONSTRAINTS: Please identify potential constraints to implement the requirement in your company	D) VALUE FOR PRODUCT DEVELOPMENT: Please describe the value of the requirement for your company. Why is this requirement important to fulfil your company product development needs to become lean?	E) STAKEHOLDERS / USERS: Please identify the potential users. You can provide name/number of persons, internal company departments, suppliers, top management, etc	F) USABILITY: Identify the degree of expertise of the users and kind of interaction with the systems in order to identify measures that minimize the effort needed for use of the solutions depending on the rank of users.	G) SUCCESS FACTORS: How can you measure the "success" of the implementation of the requirement within your company? Which could be critical success factors for the implementation	H) Additional Comments / Remarks mentioned by the Five LeanPPD industrial partners
Requirement 4: Dynamic Capture of knowledge created by engineers throughout the product development process																
4.1 The KB Environment shall provide a workspace to input different types of design knowledge to be captured, shared and utilised in real time among the development team	4	5	5	4	5	2	2	3	3	2	Company A:Types depend on the role and the task of the team member. The tool should provide a way to formalize knowledge by classifying documents according to the project phase, the project task, etc. Company B: Ability of our development/engineering processes to enable this may be a hurdle to overcome. The methodology has to seamlessly integrate with our engineering/development processes. Company D: This seems good, but what will be the checks and balances that ensure bad or misleading information is not captured and/or retained. We are not sure if it should be expert entry only, expert review, or allow knowledge to be captured by everyone (i.e. back to the WIKIPEDIA dilema.)	Company A: Templates facilitate knowledge capture and use. Moreover it supports the sharing of data from multiple perspectiCompany D, reducing communication eCompany Bors and iterations. Company B: as above Company E: A structured template which is used and equally fillde by all develepoment teams would be a fundamental step towards enterprise-knowledge-database.	Company A: Designers and Engineers coming from the different R&D departments and the Information&Technology staff Company B: as above Company E: s.a.	Company A: High level of expertise Company B: as above Company E: These interfaces should be intuitive operable.	Company A: By measuring user satisfaction and the number of questions asked by users to fullfil developed templates Company B: as above Company E: s.a.	
4.2 The KB Environment shall provide a structured template in order to capture and present in a standardised format the knowledge gained through the progression of the project	5	5	5	4	5	3	3	3	3	2	Sometimes the defined structure can be a baCompany Bier to data entry. If the structure is too ridgid and asks for information that does not seem relevant for that knowledge item, the user can be intimidated and not enter the information (i.e. the task of entering the knowledge gets put on the' Too Difficult' pile.) Company E: Knowledge is bounded to specific persons. The captured information has to be universal and must be easy to understand for everybody to become knowledge again.					
Requirement 5: The KB Environment shall provide a function to recall the key lessons learnt at the various stages of the product development process																
5.1 The Function shall provide lessons learnt, at both the systems and subsystems levels.	3	5	5	5	5	5	2	4	5	4	Company A: How to structure the lesson. The tool should provide an abstract description of the lesson learnt in order to guarantee the adaptability of the solution to specific design problems. Company B: We have an in-house lessons learned process and system. LPPD researchers will have to address this. Company D: If the data can be capture at all levels it will be easier for the user to enter the information (i.e. if the issue is related to a clip it should be stored relative to clip, not store relative to the attachment systems. i.e the system should sort out the inter-rationships not the user.) Company E: Often shortcomings are	Company A: To improve novice designers knolwedge and provide best practices to develop product design Company B: as above Company E: Another step towards enterprise-knowledge-database.	Company A: Novice designers and engineers. All R&D staff. Company B: as above Company E: Lower and higher Managers	Company A: Low level of expertise as lesson learnt can be used by non experts to improve their skill and design practice Company B: as above Company E: These interfaces should be intuitive operable.	Company A: By measuring the number of lessons retrieved for a specific problem or context Company B: as above Company E: s.a.	

Appendix B Industrial Field Study Questionnaire

Semi Structured Questionnaire for LeanPPD Field Study

Grant Agreement number:	NMP-2008- 214090
Project Title:	Lean Product and Process Development (LeanPPD)
Funding Scheme:	Large Collaborative Project
Date of latest version of Annex I against which the assessment will be made:	20.02.2009
Document Authors:	Muhammad Khan Maksim Maksimovic Rahman Alam Wasim Ahmed
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Project Website Address:	www.leanppd.eu, www.leanppd.org, www.leanppd.net
Start date of the project:	01.02.2009
Duration:	48 months
Responsible of the Document	Cranfield University Team a.al-ashaab@cranfield.ac.uk
Due Date of Deliverable	n/a
Document Ref.:	*Questionnaire for LeanPPD field study*
Version:	2
Issue Date:	07/June/2010

INTERVIEWEE DETAILS

Name	
Job Title	
Role in organisation	
Years of Experience in current role	
Previous Role(s)	
Years of experience in previous role(s)	
Tel	
Email	
LinkedIn	

CONTENTS

Introduction:

Efficient usage of product life cycle knowledge can only be accomplished, if the knowledge is captured and structured in a way that it can be formally represented and re-used within an organisation to support engineering decisions in product design and development. These procedures are defined as a Knowledge Life Cycle.

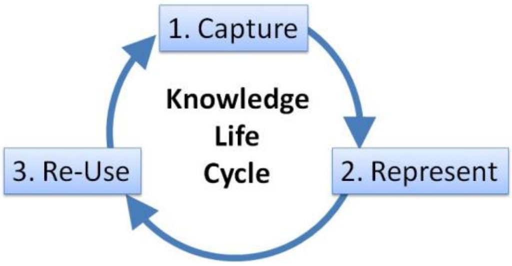


Figure 1 Knowledge Life Cycle

Knowledge Capturing

3.1. From your personal experience, how important do you assess the following sources of Knowledge?*(Select one each)*

Sources of Knowledge	**Importance**				**Comments**
	Not important	*Important*	*Very Important*	*Essential for Competitive Advantage*	
Design Rules:					
• Heuristic Rules – Company own design rules					
• Published Rules e.g. from Books					
• Rules from supplier e.g. from Material Provider					
Design Standards					
Capability of current resources					
Capability of current process					
Previous Projects					
Tacit Knowledge (Expertise of Engineers)					
Other					

3.2. Do you have formal initiatives or software(s) for capturing previous projects in a common database to provide a source of information and knowledge to support new product development? *(Select one each)*

Initiatives	Ratings				
	No Initiative & Not Interested	*Desired*	*Initiated*	*In Progress*	*Fully Established*
Lessons Learned					
CAD Files					
CAE Files					
Test Data					
BOM					
Technical Issues					
Cost Data					
Product Specifications					
Engineering Requirements					
Other					

3.3. Currently what are the implemented mechanisms to capture knowledge in your organisation and how efficient do you asses them? *(Select one each)*

Mechanisms	Usage			Effectiveness		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Verbal communication						
Questionnaires						
Document Templates						
Web-Blogs/ Notice Boards						
Other						
O We have no implemented mechanisms to capture knowledge in our organisation						

Knowledge Representation and Re-Use

3.4. What methods are used in your company to realize that captured knowledge is re-used and shared during the product development process? *(Select one for usage and effectiveness if applicable)*

Methods		**Usage**			**Effectiveness**		
		Never	*Some times*	*Always*	*Not Supportive*	*Some Content is Adequate and Supportive*	*All Content is Adequate and Essential for decision taking*
	Knowledge Based Engineering System						
	Check Lists						
	Design Templates						
	Design & Development Handbook or Manual						
	Quality Gates						
	Assessment and Judgement from Experts in your Organisation						
	Wikis						
	Web Servers / Intranet						
	E-Books						
	Reports						
	other						

3.5. How do you assess the importance of proven knowledge (e.g. test results) to support decision taking in product design and development? *(Select one)*

Not Important	Important	Very Important	Essential for any decision

3.6. In general any product development task consists of two key elements; routine tasks and innovative tasks.

- The routine tasks, is standard and done for all products; as most of the product are not developed from scratch rather they are successive from previous designs
- Innovative tasks distinguish the new product from previous ones and have not been considered before.

The following picture represents a common distribution:

Please estimate in percentage how much of your work is related to routine and innovative Tasks? *(Select one)*

	100% routine - 0% innovative
	80% routine - 20% innovative
	60% routine - 40% innovative
	50% routine - 50% innovative
	40% routine - 60% innovative
	20% routine - 80% innovative
	0% routine - 100% innovative

3.7. Please estimate how much, in percentage, do you rely on knowledge from previous project when designing a new product? *(Select one)*

	100%
	80%
	60%
	50%
	40%
	20%
	0%

3.8. What specific knowledge domain do you need for your regular engineering activities? *(Select one each)*

	Importance		
Domain	*Not Important*	*Important*	*Very Important*
Injection Moulding			
Stamping			
Machining			
Casting			
Other			

3.9. From your personal experience, which of the following activities would you consider to be important for engineering decision taking? *(Select one each)*

	Importance		
Activities	*Not Important*	*Important*	*Very Important*
Definition of Product Specifications			
Design for Manufacture and Assembly			
POKA YOKE – Mistake Proofing			
Tooling Design			
Cost Calculation			
Production Planning and Scheduling			
Testing and Simulations			
Other			

3.10. Which commercial software do you use to support product development?

Software for:	*Commercial Software (e.g. Catia V5)*	*Release (e.g. R14)*
Product Lifecycle Management (PLM)		
Computer Aided Design (CAD)		
Product Data Management (PDM)		
Enterprise Resource Planning (ERP)		
Knowledge Based Engineering (KBE)		
Computer Aided Engineering (CAE), e.g. CFD, FEA etc.		
Computer Aided Manufacturing (CAM)		
Cost Calculations		
Quality Management		
Other		

3.11. What is your experience in using the following acclaimed commercial Knowledge Based Engineering systems? (If used select one and rate experience)

Used	**Knowledge Based System**	**Experience**			
		Bad – Not Useful	Occasionally Beneficial	Very Good - Recommended	Comments
	AML - TechnoSoft Inc				
	DriveWorks - SolidWorks				
	Knowledge Fusion - UG				
	Knowledgeware - Catia				
	Expert Framework - ProEng				
	Siemens Teamcenter – Enterprise Knowledge Foundation				
	PACE KBE Platform				
	other				
	I have not used any Knowledge Based Engineering system before				

3.12. How and which of the following data is stored at your company for a specific product during the entire product life cycle? *(If used select one or multiple for storage)*

No.	**Used**	**Data**	**Storage Form**				
			Paper Form	PDM Database	ERP	Share Drive	*Other*
1		QfD					
2		BOM					
3		Cost Calculations					
4		Make or Buy					
5		RfQ					
6		Specifications Documents					
7		CAD Models					
8		CAD Drawings					
9		CAE Files					
10		DFMEA					
11		Test Reports					
12		Design Validation Reports					
13		Capacity Planning					
14		PFMEA					
15		PSW					
16		PPAP Documents					
17		Process Capability					
18		Resource Capability					
19		Change Requests					
20		Customer Satisfaction Reports					
21							
22							

3.13. Do you think that problems in previous designs could have been prevented by the correct knowledge being provided at the right time?

none	O	O	O	O	All

3.14. What challenges do you face with regards to managing product development knowledge? (you may select more than one option)

Options	
	Often very time-consuming
	Incompatibility of knowledge formats between different software
	Unnecessary knowledge capture and over-crowded documents/figures/posters/databases etc.
	Designers find it difficult to extract knowledge from previous projects

Appendix C A Method for Knowledge Maintenance during Knowledge Integration: Stage 5 of the LeanKLC

Section 5.5.5.4 explained how provided knowledge perceived a usefulness evaluation using a Likert scale. In time however, the collection of several feedback scores results in reflective patterns of which meaningfulness requires interpretation. The primary interpretation is based on numerical rating methods for the collected feedback data which include trigger, average and linear regression.

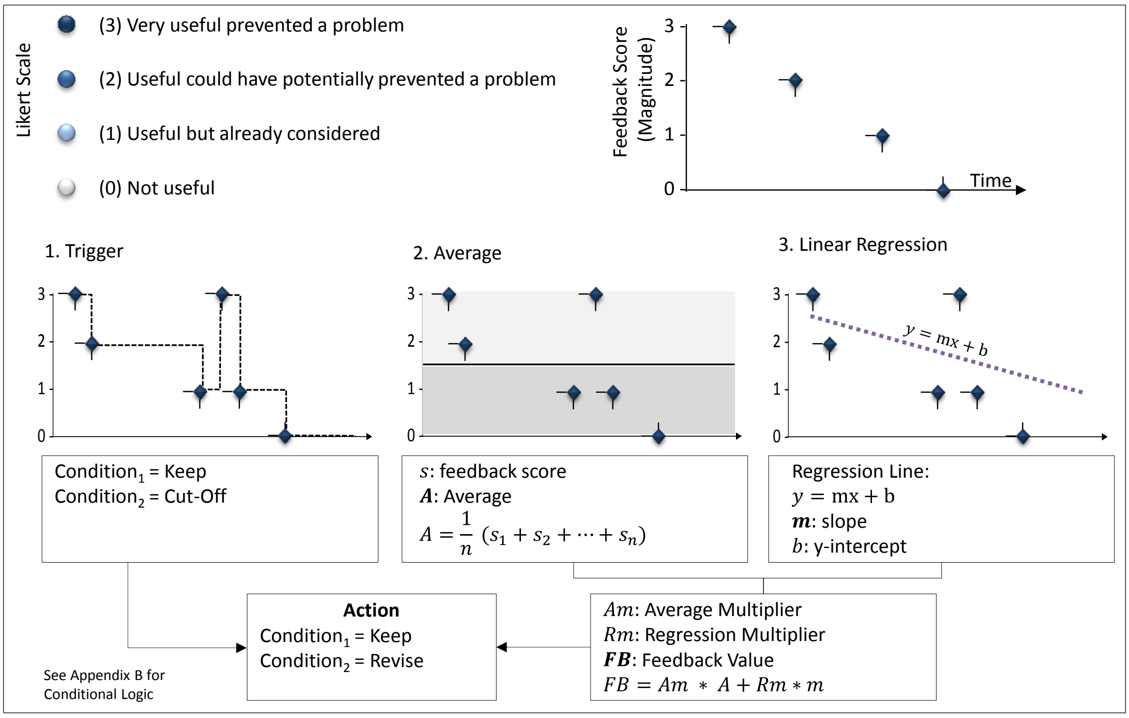


Figure 7.1 Feedback Rating Methods for Provided and Re-used Knowledge based on usefulness Evaluation

Figure 7.1 illustrates the different rating methods and their implication on a given feedback scenario pattern. It shows that different rating methods provide different results on the same pattern; as such the following will describe in detail the rating methods as well as the implications of different scenario patterns. The rating methods are supported by its functional logic in BASIC programming language and are included in Appendix C.1 to C.5.

As shown in Figure 7.1, the trigger rating method is counting single feedback scores and provides only absolute values for a series of feedback scores. Its purpose is to alarm on low rating scores. For example, if a feedback score was rated “0” three times in a period of six months and an adequate amount of feedback scores were collected it shall advise to “Cut-Off” the knowledge. In other words, the knowledge was primarily rated not useful and therefore doesn’t need any further consideration for re-use. Any other constellation results in the trigger value to “Keep” the knowledge. Therefore, trigger function results in two feedback score interpretations, which are “Cut-Off” or “Keep” depending on conditional values, as illustrated in Figure 7.2.

The average function calculates the average of the overall collected feedback scores for a particular knowledge in re-use. As shown in Figure 7.1, the average rating is represented as a horizontal line, which means that value over time is not taken into consideration. Therefore, linear regression is used to evaluate a trend of feedback scores as a value over time. This is accomplished by using the slope value in order to determine a trend regarding how the knowledge performs in future aiming at discarding or prioritising knowledge upfront. However, obtaining meaningful values requires a minimum sample collection as well a period of time. For example, if the first scoring of the knowledge was rated “0” and the second rating was “3” within a short time period, the slope results in a misleadingly high value.

The feedback value provides the ultimate value to determine usefulness of knowledge. The feedback value shall equal to the highest rated in the knowledge base for an initial amount and time in order to prioritise present knowledge. Once the initial amount of re-use is accomplished the feedback score is calculated by using multipliers for the average as well as for the regression value, as shown in Figure 7.1. These multipliers are declared in order to provide an adjustable feedback evaluation according to different product development operating environments. The final verdict of the value is given by the “action” function which determines two conditional values, namely “revise” or “keep”. Revision of knowledge shall occur when the trigger value equals “cut-off” or when the feedback score is equal or below a pre-defined critical feedback value. In order to define adequate multipliers for the regression and average value as well as definition of critical feedback value, common scenario patterns are created in order to exemplify the adjustment accordingly.

As shown in Figure 7.2, patterns are mapped on a graph which consists of a one year time frame (twelve months). Each pattern has the same time distribution of feedback collected, though differentiating within the score given. The conditional values for each rating method are displayed in the left top corner in Figure 7.2. The different scenario patterns have been identified as a result of industrial collaboration and include low score, high score, fluctuation, decrease and increase. Below each scenario pattern the values of the different rating methods are displayed. Trigger, for example, has two possible values, either “Cut-Off” or “Keep”. Regression value on the other hand represents the slope of the regression line. Feedback represents the final value for the knowledge and action suggests either keeping or revising the knowledge. The following describe the implications of different rating methods to the scenario pattern and advices how to adjust the feedback value accordingly.

The low score pattern describes a scenario where the knowledge is rated low, at the beginning of knowledge re-use for several months. This means that the knowledge is regarded as low value for the engineers. In this case, the trigger value shall indicate that the knowledge needs to be cut-off, therefore it advises to revise the knowledge. The resulting feedback score should be close to the average; hence there is low fluctuation.

The scenario illustrated in Figure 7.2 as high score, represents a pattern where feedback is scored very high from the beginning. Most of the time engineers rated the knowledge as very useful; hence it potentially or actually prevented a problem. Knowledge is from high value and therefore a high feedback score should ensure that this knowledge is put forward during knowledge provision. As in the low score example, the feedback score should be close to average as there is low fluctuation and action should recommend keeping the knowledge for provision.

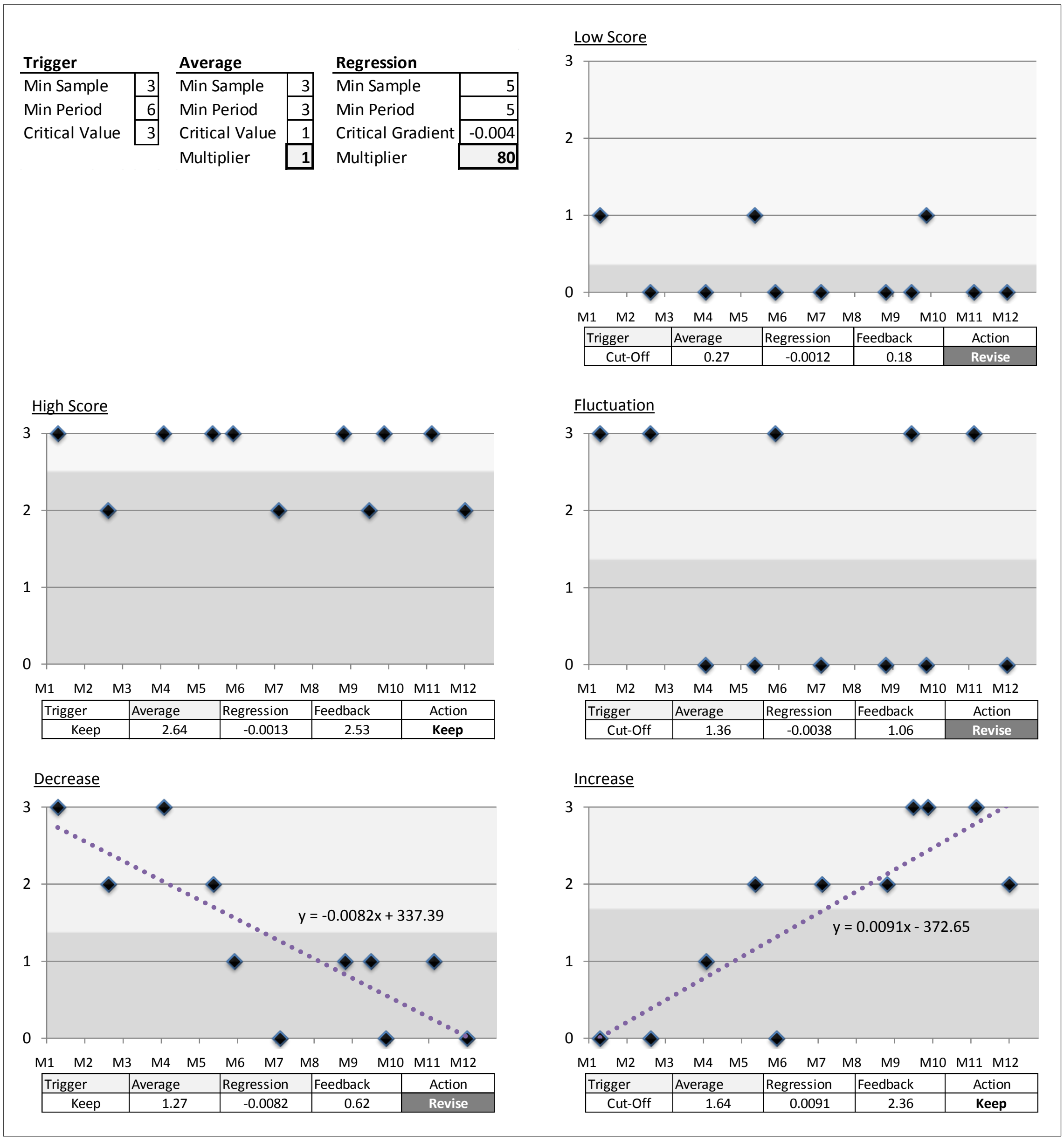


Figure 7.2 Feedback Score Adjustment based on usefulness Evaluation over Time

The fluctuation pattern as shown in Figure 7.2, refers to a scenario where the knowledge is scored with a high fluctuation between very useful (score3) and not useful (score0). Reasons for that are different perspectives between engineers. The Knowledge is definitely important; hence, it prevented recurrence of design problems in several incidents. However, it would be suggestive to investigate who rated this Knowledge low. Most probably, it applies only to a very specific product range, activity or engineers and therefore reconsideration of the knowledge needed P_{nd} coordinate is suggested. As such, despite an acceptable average value, the action should suggest 'revise', resulting from the trigger value due to several '0' ratings.

The pattern of decrease illustrates a scenario where knowledge is losing value in time. A reason for such a pattern is that requirements or technology for a particular knowledge domain become out of date. The feedback mechanism is recognising a negative trend through the slope of the linear regression, illustrated as a decreasing trend line in Figure 7.2. Hence, the feedback score needs to result in a lower value than the average in order to provide evidence about the decreasing trend. Consequently, action should suggest revising the knowledge to identify and discard upfront decreasing knowledge.

The final pattern outlined is a scenario where knowledge is rated low at the start but increases in time, shown in Figure 7.2 as increase. The reason for such a pattern is the introduction of knowledge related to a new technology that is not well established. This means that knowledge gains more acceptance in time as engineers use it more frequently. During the first knowledge provision activities knowledge is rated very low, which results that the trigger-value suggests a cut-off. However, the gradient of the regression analysis increases in time to such an extent that the feedback value exceeds the average value. This means that the gradient of regression analysis will ensure that despite the low score start, as a result of low level knowledge acceptance, the knowledge can at some point reach the same feedback score as knowledge rated high from the start. The above exemplified the adjustment of feedback scores according to given scenarios. Companies adapting the feedback mechanism should map these scenario patterns according to the operating environment meaning that timely distribution of feedback collected changes within different industries.

C.1 Trigger Function

```
Function Trigger(rangefb, rangetime, trigMinSample, trigMinPeriod, trigFbCritical, trigFbCritoccur)

fbCount = Application.Count(rangefb)
‘Calculates the total amount of feedback collected
fbDuration = Application.Sum(rangetime)
‘Calculates the total duration of feedback collection
fbMinCount = Application.Countif(rangefb, trigFbCrititcal)
‘Counts the amount critical trigger value was rated

If fbCount >= trigMinSample And fbDuration >= trigMinPeriod And fbMinCount >= trigFbCritoccur Then
Trigger = “Cut-Off”
Else
Trigger = “Keep”
End If

End Function
```

C.2 Average Function

```
Function Average(rangefb)

Average = Application.Average(rangefb)
'Calculates the average of feedback collected

End Function
```

C.3 Regression Function

```
Function Regression(rangefb, rangetime, regMinSample, regMinPeriod)

fbCount = Application.Count(rangefb)
'Calculates the total amount of feedback collected
fbDuration = Application.Sum(rangetime)
'Calculates the total duration of feedback collection

If fbCount >= regMinSample And fbDuration >= regMinPeriod Then
Regression = Application.Linest(rangefb, rangetime)
'Calculates the gradient of the 1st level interpolation
Else
Regression = 0
End If

End Function
```

C.4 Feedback Score Function

```
Function Feebackscore(rangefb, rangetime, entirerange, fbscoreMinSample, fbscoreMinPeriod
averagevalue, regressionvalue, avmultiplier, regmultiplier)

fbCount = Application.Count(rangefb)
'Calculates the total amount of feedback collected
fbDuration = Application.Sum(rangetime)
'Calculates the total duration of feedback collection
maxscore = Application.Max(entirerange)
'Sets the variable to the maximum feedback score in the knowledge base

If fbCount <= fbscoreMinSample And fbDuration <= fbscoreMinPeriod Then
Feedbackscore =  maxscore
Else
Feedbackscore = averagevalue * avmultiplier + regressionvalue * regmultiplier
End If
End Function
```

C.5 Action Function

```
Function Action(triggervalue, fbscore, fbcritical)
If triggervalue = "Cut-Off" Or fbscore <= fbcritical Then
Action = "Revise"
Else
Action = "Keep"
End If
End Function
```

Appendix D Monitor the LeanKLC through Qualitative Assessment

The establishment of knowledge management continuity in product development is very difficult, as outlined in Chapter 4. Organisations usually start undergoing a number of knowledge management related initiatives, however successful continuation is rare mainly due to the lack of motivation and consistency. For this reason it is suggested to monitor the performance of LeanKLC application through qualitative assessment. This research did not develop a methodology and framework for performance assessment, although it adapts the lean assessment tool as established during the LeanPPD project and suggests key practices for qualitative assessment seen as adequate for the LeanKLC.

	LeanPPD Self-Assessment - Maturity Level
1	No Lean Thinking with Some Awareness (Start)
2	Getting Started (Motivate)
3	Basic LeanPPD (Apply)
4	LeanPPD continuously Measured and Improved (Review and Improve)
5	LeanPPD Best Practice Identified and Shared (Transform)

Qualitative Assessment against LeanPPD Maturity Level.

Definition of practices for each stage of LeanKLC application (e.g. Knowledge Sharing).

4.1	**Knowledge Sharing - Appoint Knowledge Owners - Skill Directory**	**As-Is**	**To-Be**	**Relev**
1	Domain experts are not willing to share knowledge			
2	Domain experts are willing to share knowledge, however there is no skill directory			
3	A skill directory exists only in particular departments	**1-5**	**1-5**	**1-5**
4	A corporate skill directory exists, however it is difficult to find the right person			
5	A corporate skill directory exists and it is easy to find the right person			

Figure 7.3 Example of LeanKLC Practices and Qualitative Assessment

As illustrated in Figure 7.3, the qualitative assessment of the lean assessment tool comprises five maturity levels, ranging from 1 (Start- No Lean Thinking with some Awareness) to maximum 5 (Transform- LeanPPD best practice identified and shared). The maturity level is assessed as an As-Is and To-Be state, so companies can compare their current status as well as set a target desired to be achieved in future. The assessment also includes the relevance rating in order to prioritise among different performance indicators. Figure 7.3 illustrates the practices as elaborated for the LeanKLC stage of knowledge sharing for the task related to appointing knowledge owners, as described in 5.5.4.1.2. Hence, if a company chooses to undergo this task, it can assess its current performance and compare it against best practice. At some point in time, the company can track their improvement against the envisioned To-Be. This form of qualitative assessment is seen as important to maintain as well as enforce the successful transformation towards a knowledge environment in LeanPD using the LeanKLC. The following presents a selection of LeanKLC practices to be assessed as elaborated by the author throughout the research project.

1	**Knowledge Life Cycle**	**As-Is**	**To-Be**	**Relev**
1	The systematic creation of knowledge is not part of our corporate philosophy			
2	We realise that Knowledge capture, reuse and creation is important, but we haven't got yet any framework			
3	We initiated once a framework for knowledge capture, re-use and creation	**1-5**	**1-5**	**1-5**
4	A framework for knowledge capture, re-use and creation exists in the company			
5	We have a fully established framework for knowledge capture, re-use and creation			

2	**Identification of Knowledge**	**As-Is**	**To-Be**	**Relev**
1	We do not practise to identify the useful knowledge			
2	The identification of the useful Knowledge is based on personal intuition			
3	A list of useful knowledge sources is provided to the PD engineers	**1-5**	**1-5**	**1-5**
4	Useful Knowledge is identified across the entire enterprise			
5	Useful Knowledge is identified across the entire enterprise and supports knowledge capturing			

3	**Decisions in Product Development are mainly based ...**	**As-Is**	**To-Be**	**Relev**
1	... on Knowledge from personal perspective			
2	... on Knowledge obtained in the operating function			
3	... on Knowledge obtained in the operating and another function	**1-5**	**1-5**	**1-5**
4	... on Knowledge obtained in the operating and multiple other functions			
5	... on Knowledge obtained in the operating and multiple other functions, but also from previous projects			

4	**Product Development Knowledge is stored in ...**	**As-Is**	**To-Be**	**Relev**
1	... various places and formats			
2	... share drives			
3	... a PDM system	**1-5**	**1-5**	**1-5**
4	... a well structured PDM system			
5	... a well structured and centralised PDM system with access to multiple sources			

5	**Product Development Knowledge is structured according ...**	**As-Is**	**To-Be**	**Relev**
1	... personal perception			
2	... project related milestones			
3	... project related milestones & functions	**1-5**	**1-5**	**1-5**
4	... project related milestones, functions and product level			
5	... project related milestones, functions, product and component level			

6	**Once Knowledge is captured it is ...**	**As-Is**	**To-Be**	**Relev**
1	... never used again			
2	... hardly ever used again			
3	... re-used for a certain range of PD engineering activities	**1-5**	**1-5**	**1-5**
4	... re-used for a certain range of PD engineering activities across functions			
5	... re-used for a range of PD engineering activities across functions			

7	**Knowledge is usually shared ...**	**As-Is**	**To-Be**	**Relev**
1	... through verbal communication or e-mails			
2	... during face to face meetings			
3	... during stage gate review meetings	**1-5**	**1-5**	**1-5**
4	... during stage gate review meetings and documented			
5	... during stage gate review meetings, documented and stored in centralised location			

8	**Knowledge Sharing - Appoint Knowledge Owners - Skill Directory**	**As-Is**	**To-Be**	**Relev**
1	Domain experts are not willing to share knowledge			
2	Domain experts are willing to share knowledge, however there is no skill directory			
3	A skill directory exists only in particular departments	**1-5**	**1-5**	**1-5**
4	A corporate skill directory exists, however it is difficult to find the right person			
5	A corporate skill directory exists and it is easy to find the right person			

9	Routine and Innovative Tasks	As-Is	To-Be	Relev
1	I purely spend my time on routine tasks			
2	I spend 80% of my time on routine tasks, the remaining is spend on innovative tasks			
3	I spend 60% of my time on routine tasks, the remaining is spend on innovative tasks	**1-5**	**1-5**	**1-5**
4	I spend 40% of my time on routine tasks, the remaining is spend on innovative tasks			
5	I spend 20% of my time on routine tasks, the remaining is spend on innovative tasks			

10	During Product Development Engineers receive…	As-Is	To-Be	Relev
1	… no additional knowledge			
2	… Check-Lists			
3	… updated Check-Lists	**1-5**	**1-5**	**1-5**
4	… updated Check-Lists and Visual Graphs			
5	… updated Check-Lists, Visual Graphs in a Design Notebook			

11	During Product Development Knowledge is provided…	As-Is	To-Be	Relev
1	… never			
2	… too late, when key decisions are already made			
3	… at the right time	**1-5**	**1-5**	**1-5**
4	… at the right time and place			
5	… at the right time, place and form			

12	Previous Projects Knowledge is used to …	As-Is	To-Be	Relev
1	… document only			
2	… initiate one potential design solution			
3	… sometimes initiate multiple design solution during concept selection	**1-5**	**1-5**	**1-5**
4	… always initiate multiple design solution during concept selection			
5	… always initiate multiple design solution and eliminate weakest ones as we proceed			

13	Lessons Learnt are captured…	As-Is	To-Be	Relev
1	… not in my department			
2	… long time after the project has finished			
3	… at the end of a project	**1-5**	**1-5**	**1-5**
4	… during selected stage gate reviews			
5	… dynamically whilst created			

Appendix E A3LAMDA Pilot-Reports in Case Study 1 at Company A

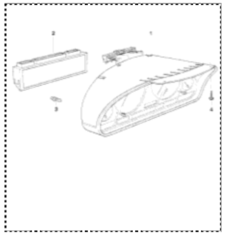
Page No.	A3LAMDA Pilot Report No.
250	A3_1
251	A3_2

1. Team: AK, KS, & MS **Author:** AK **Date:** 22/10/1010

Title: Radiated Emission (RE) Test **A3 Report No:** A3_1

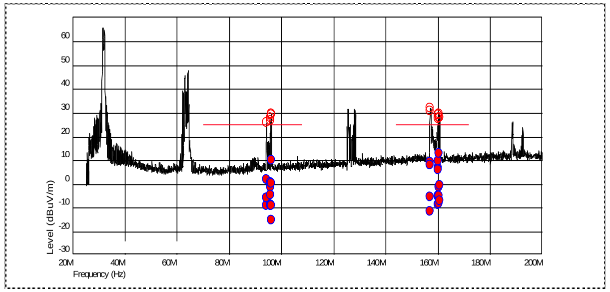
2. Background

Product Type	Instrument Cluster
Product Name	ClusterA
Product Code	XXP1
Software No.	XXS1
PCB No.	XXPCB1
Serial No	XX1
Customer Spec	A
Other Information:	



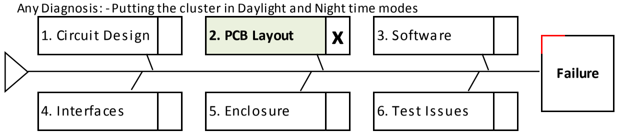
3. Current Condition

Test Request No	XTRQ1	Funct Status	I
Test Report No	XTRP1	Funct Perform Class	A
Test Type	RE XX	Occurrence	1
Other Information: The constant current drive circuit for the gauge illumination going into positive feedback and radiated at 31.4MHz.			



4. Root Cause Analysis

Any Diagnosis: - Putting the cluster in Daylight and Night time modes

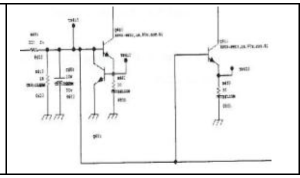


No	Potential Causes	Reasons
2.1	Gauge illumination	-Daylight operating mode = OFF, Night time operating mode = ON
		-Capacitor-X was incorrectly positioned in PCB layout.

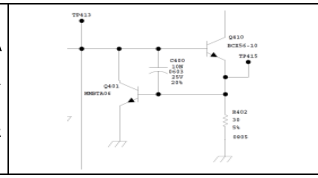
5. Proposed Solution

No	Solutions	Type		Effectiveness		
		Temp	Perm	Not	SW	Very
2.1	Put the capacitor-X close to the constant current drive circuit and between the base and collector of voltage clamping transistor.		X		X	

BEFORE



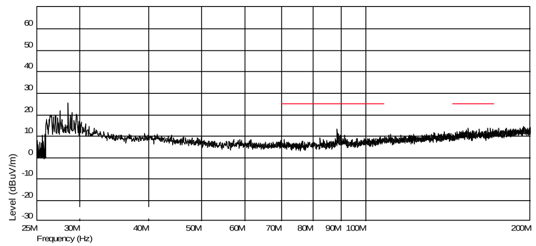
AFTER



6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
2.1.1	Redesign	Put capacitor-X close to constant current driven circuit and between the base and collector of voltage clamping transistor.	Detail EMC Designer (1 Week)
2.1.2	Re-Test	The modified design for XCAR cluster performs the RE test.	EMC Test Eng. (2 weeks)

Result: The modified XCAR design cluster is Passed



7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?	X		the constant current drive circuit will possibly go into positive feedbacks and so a capacitor -X is required to slow the response of the voltage clamping transistor to the PWM signal input on the base.
2. Any consequences to other products/processes?	X		On any constant current drive circuit it should package protect for a capacitor-X close the clamping to stop the positive feedback should be captured in the schematic and the layout document.

8. What

No	Lessons Learnt
1	The placing of the capacitor-X close the clamping transistor to stop the positive feedback.

9. So What

Type of Knowledge		Design Issues: Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Design Rule	1							
Put the capacitor-X close to the constant current drive circuit and between the base and collector of voltage clamping transistor Y.		X						
Recommendation	2							
Implement the constant current drive circuit to ensure the illumination is stable.			X					
	3							

10. Now What

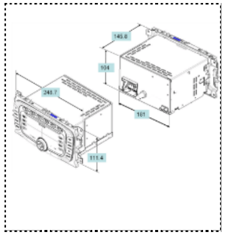
DR / Rec	Activity
DR1	Schematic Design and Approval (41)
Rec2	Create Electrical BOM (45)

1. Team: MS, MB, MA and IP **Author:** MS **Date:** 15/06/2011

Title: RI XX FM SINAD **A3 Report No:** A3_4

2. Background

Product Type	Audio
Product Name	AudioA
Product Code	XXP2
Software No.	XXS2
PCB No.	XXPCB2
Serial No	XX2
Customer Spec	A
Other Information:	



3. Current Condition

Test Request No	XTRQ2	Funct Status	II
Test Report No	XTRP2	Funct Perform Class	A
Test Type	RI XX	Occurrence	1
Other Information:			

Observations
Band 5B, FM mode.
Orientation X
Vertical
SINAD failure at 1760MHz, 29V/m PM.
SINAD failure at 1780MHz, 24V/m PM.
SINAD failure at 1800MHz, 25V/m PM.
SINAD failure at 1820MHz, 33V/m PM.
SINAD failure at 1840MHz, 36V/m PM.
SINAD failure at 1860MHz, 45V/m PM.
SINAD failure at 1960MHz, 45V/m PM.
SINAD failure at 1980MHz, 45V/m PM.
SINAD failure at 2000MHz, 41V/m PM.
Orientation Z
Vertical
SINAD failure at 1700MHz, 44V/m PM.
SINAD failure at 1720MHz, 36V/m PM.
SINAD failure at 1740MHz, 36V/m PM.
SINAD failure at 1760MHz, 43V/m PM.
SINAD failure at 1780MHz, 32V/m PM.
SINAD failure at 1800MHz, 32V/m PM.
SINAD failure at 1820MHz, 40V/m PM.
SINAD failure at 1840MHz, 40V/m PM.
SINAD failure at 1860MHz, 45V/m PM.
Horizontal
SINAD failure at 1780MHz, 31V/m PM.
SINAD failure at 1800MHz, 35V/m PM.

Observations
Band 5B, FM mode.

Orientation Y
Vertical
SINAD failure at 1720MHz, 45V/m PM.
Horizontal
SINAD failure at 1780MHz, 44V/m PM.
SINAD failure at 1800MHz, 34V/m PM.

Orientation Z
Vertical
SINAD failure at 1800MHz, 40V/m PM.
Horizontal
SINAD failure at 1780MHz, 34V/m PM.
SINAD failure at 1800MHz, 28V/m PM.
SINAD failure at 1820MHz, 39V/m PM.

4. Root Cause Analysis

1. Circuit Design
2. PCB Layout X
3. Software
4. Interfaces
5. Enclosure
6. Test Issues

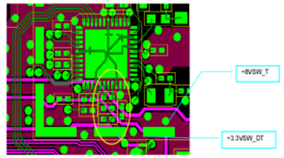
RI114 SINAD Failure

No	Potential Causes	Reasons
2	Tuner layout	The plane is broken by two power supply tracks (+8xxx_T and +3.3xxx_DT).
		The +3.3xxx_DT line is open at both ends. The length of the 3.3xx track is approximate 3in at 1.8Hz.
		Data Tuner +3.3xxx_DT is not fitted.
		Length of the of track.

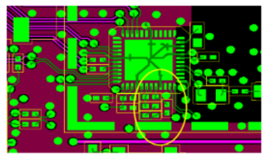
5. Proposed Solution

No	Solutions	Type: Temp	Type: Perm	Effectiveness: Not	Effectiveness: SW	Effectiveness: Very
2.1	Bypassing diplexer	X		X		
2.2	Tuner shield fit it properly		X		X	
2.3	Cable layout for test	X			X	
2.4	To fit the Cxx and Cyy to reduce the impedance on the length of track.	X				X

BEFORE



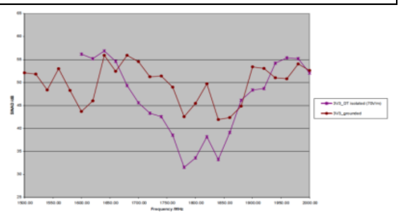
AFTER



6. Implementation Plan

No	Tasks	Actions to Implement Proposed Solutions	Resp & Duration
2.4.1	Redesign	Fiting the 0 ohm links both Cxx and Cyy	Plant - 2 weeks
2.4.2	Retest	The test is repeat and performance is to be confirmed.	PA Eng & EMC Test Eng -1 week

Result: The modified unit seemed to show less degradation in the 1700-1900MHz frequency range.



7. Prevent Recurrence

Questions to prevent Recurrence	Y	N	Descriptions & Actions to Prevent Recurrence
1. Does the solution impact other EMC tests?	X		RI YY was performed to ensure FM performance is maintained. RE XX was performed to ensure hardware change does not affect emissions.
2. Any consequences to other products/processes?		X	

8. What

No	Lessons Learnt

9. So What

Type of Knowledge	Circuit Design	PCB Layout	Software	Interfaces	Enclosure	Test Issues	Other
Recommendation 1 The layout engineer should ensure that the tracks does not run under sensitive circuit.		X					
Recommendation 2 The schematics should identify the sensitive parts of circuit.	X						
Recommendation 3 Need to review the impact of the depopulating and components				X			

(Design Issues)

10. Now What

DR / Rec	Activity
Rec1	Electrical Engineering
Rec2	Electrical Engineering
Rec3	Electrical Engineering